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# THE DISAPPEARING-FILAMENT OPTICAL PYROMETER CALIBRATION AND USE

W. E. FORSYTHE AND E. Q. ADAMS*

*Received December 21, 1944; published August 29, 1945*

## INTRODUCTION

Many of the processes in modern industry require very close and very constant control of temperature. Without going into detail, this occurs in the iron and steel industry, the making of many ceramic products, such as glass, and in many of the processes of reducing metals from their ores.

The ordinary method of measuring temperature is to place the measuring device in very close contact with the body of which the temperature is desired. For such work at low temperatures, ordinary mercury-in-glass thermometers, other materials in glass or quartz tubes, thermocouples, or resistance thermometers are used. As the temperature is increased to higher and higher values, a temperature is soon reached which is higher than the insertion types of measuring devices can stand for any length of time and maintain their calibration. Indeed, many operations require temperatures that are so high that most of the insertion temperature-measuring devices would be completely destroyed. Many of the substances whose temperatures must be measured; e.g., molten iron or molten glass, have such violent reaction with other materials at these high temperatures that it is very difficult to get anything that can be used as a protective tube for the insertion type of temperature measuring device. Also, occasionally, it is necessary to measure the temperature of a source that is so small or so situated that it would be difficult to bring a measuring instrument into direct contact with the source. When any of these conditions exist, advantage is taken of the well-known fact that all bodies when at sufficiently high temperatures send out radiation in amounts readily measurable. The intensity of this radiation has been found to have a definite relation to the temperature for any one material when it is brought to the same surface conditions. However, the only body for which the relation between the temperature and the intensity of the radiation is known from theoretical consideration is the blackbody.

## THE BLACKBODY

A blackbody is one that absorbs all radiation that falls upon it, neither reflecting nor transmitting any of the incident radiation. It can be shown that a cavity with walls at uniform temperature contains blackbody radiation of the same

* General Electric Company, Nela Park, Cleveland, Ohio.

temperature as the walls. If a small opening—small with respect to the wall area—is made into this cavity, the radiation escaping from this opening will be the same as that within the cavity.

The total radiation given by a blackbody is related to the temperature by the Stefan-Boltzmann formula, which is

$$W = \sigma T^4 \tag{1}$$

where $W$ is the total energy radiated in unit time by the blackbody of unit area at temperature $T$, $\sigma$ being the experimental constant.

The distribution of energy in the spectrum of the radiation from a blackbody is given by Planck's formula.

$$J_\lambda = \frac{A \cdot c_1 \lambda^{-5}}{e^{\frac{c_2}{\lambda T}} - 1} \tag{2}$$

where $J_\lambda$ is the intensity of the radiation, $c_1$ and $c_2$ are constants determined experimentally, and $e$ is the base of Naperian logarithms. For values of the

TABLE 1

*Energy ratios and corrections to temperatures as calculated with Wien's equation to reduce them to what would be obtained from Planck's equation for* $\lambda = .665\mu$ *and* $c_2 = 14320\mu°$ *for definite values of brightness*

| TEMPERATURE IN °K | $\lambda T$ | ENERGY RATIOS *Ep/Ew* | CORRECTIONS TO TRUE TEMPERATURE |
|---|---|---|---|
| 2000 | 1330 | 1.00002 | −<0.01°K |
| 2500 | 1662 | 1.00018 | −0.05 |
| 3000 | 1995 | 1.00076 | −0.3 |
| 3500 | 2328 | 1.0021 | −1.2 |
| 4000 | 2660 | 1.0046 | −3.4 |
| 4500 | 2992 | 1.0084 | −8.5 |
| 5000 | 3325 | 1.0137 | −15.5 |
| 6000 | 3990 | 1.0284 | −45.2 |

product $\lambda T$ less than about 3000 this equation can be replaced by Wien's formula which gives the spectral distribution with an error of less than one percent. Wien's formula is

$$J_\lambda = \frac{A c_1 \lambda^{-5}}{e^{\frac{c_2}{\lambda T}}} \tag{3}$$

This form is much easier to use in calculations than Planck's more exact form; thus it is always used in calculations that have to do with the calibration of optical pyrometers. The results thus obtained are sufficiently accurate for this purpose, except at very high temperatures, because, as the pyrometer is used, the product $\lambda T$ is always less than 3000.

The results given in Table 1 show just what errors may result from the use of Wien's formula for such calculations.

In what follows in the next several pages it is to be assumed that the source under investigation and the source against which the pyrometer is calibrated is the standard cavity-type blackbody. The relation between temperature and radiation intensity for non-blackbodies will be discussed later.

## HIGH-TEMPERATURE PYROMETRY

The temperatures of very hot bodies have probably always been judged by direct eye observation (Fig. 1) of the color or brightness of the light given off.

With practice, one can estimate probably within 50° to 100°C of the correct value. However, if judgment is left to the eye alone, very much larger errors may sometimes be made, because the eye is not a very reliable instrument for making absolute measurements of the intensity of light and this accuracy may be further reduced, due to the use that has been made of the eye just previous to the

FIG. 1. The first optical pyrometer
(Courtesy of H. T. W.)

time of estimating. However, the eye is very sensitive to differences in brightness between two adjacent surfaces, and hence eye observations can be used to tell very accurately when two adjacent surfaces are at the same brightness. Thus, to secure accurate estimates by eye, a comparison source is necessary. The introduction of a comparison source is the first step toward an optical pyrometer, which consists of a comparison source and some convenient arrangement for matching this source, either in brightness or in color, against the source studied.

An outstanding advantage of the optical pyrometer is the ratio of the change in temperature to the change in brightness for the blackbody. As shown in Table 2 this ratio varies from about 18 at 1200°K to about 7 at a temperature of 3000°K. This means that an error of one percent in measuring the brightness would result in an error of one-eighteenth of one percent—about 0.7°—at 1200°K and one-seventh of one percent—about 4°—at 3000°K. With good conditions

for such work, brightness matches can be made to a fraction of one percent, probably about two- or three-tenths of one percent.

### THE TEMPERATURE SCALE

The temperature scale is based on the temperature interval between melting ice and boiling water under standard conditions. On the centigrade scale this interval is taken as 100 degrees. For temperatures above the gold point, 1336°K, the high temperature region,* "the temperature $T$ is determined by means of the ratio of the intensity $J_2$ of monochromatic visible radiation of wavelength $\lambda$ emitted by a blackbody at the temperature $T$, to the intensity $J_1$ of radiation

TABLE 2

*Ratios of the percent changes in red brightness to the percent change in temperature of a blackbody for a number of temperatures*

| Temperature | 1200 | 1500 | 2000 | 2500 | 3000 |
|---|---|---|---|---|---|
| Ratio | 17.9 | 14.3 | 10.7 | 8.6 | 7.2 |

TABLE 3

*Standard temperatures above the gold point**

| | |
|---|---|
| Freezing Palladium | 1827°K |
| Freezing Platinum | 2046 |
| Freezing Rhodium | 2239 |
| Freezing Iridium | 2727 |
| Freezing Tungsten | 3645 |
| Carbon Arc | 3820 |

* These values are based upon the gold point, 1336°K, and $c_2 = 14320\mu°$.

of the same wavelength emitted by a blackbody at the gold point, by means of the formula"—

$$\log \frac{J_2}{J_1} = \frac{c_2 \log e}{\lambda}\left[\frac{1}{1336} - \frac{1}{T}\right] \tag{4}$$

This formula, derived from Wein's formula, is used in the calculations appertaining to the calibration of optical pyrometers.

There are several fixed points in the high-temperature region that have been well determined. Some of these are given in Table 3.

### THE SECOND RADIATION CONSTANT, $c_2$

As shown by formula 4, the only constant that enters into the calibration of the optical pyrometer as it has been used is $c_2$, the so-called second radiation constant. It seems that a variation of this constant will always be with us.

* Definition of International Temperature Scale.

The value of this second radiation constant can be determined in two ways, by direct measurement and by calculation from its relation to other physical constants.

Up until about 1915 or 1916 the value used in this country for $c_2$ was 14500 $\mu°$, and about this time some new work indicated a change in the value was necessary.

Coblentz[1] in 1913 made an analysis of all the experimental values of $c_2$, including of course his own, and arrived at the best average of 14456 $\mu°$. In the second paper on this subject in 1916 he gave as the best average 14350 $\mu°$, and in 1922 experimental results indicated this value should be 14318 $\mu°$. In 1923 the editor of the International Critical Tables adopted the value of 14326 $\mu°$ to use for calculating data for these tables.

Birge[2] has made several summaries of the various physical constants in which he gives the calculated value of $c_2$. In 1919 he gave a value of 14319 $\mu°$; in 1926, 14328 $\mu°$; and in the general summary of Physical Constants, published in 1929, 14317 $\mu°$. This had increased to 14335 $\mu°$ in 1932, and in 1941 Birge published another general summary of Physical Constants in which he gave 14384 $\mu°$ as the value of $c_2$.

TABLE 4

*Values of $c_2$ used at different times*

| DATE | NATIONAL BUREAU OF STANDARDS | NELA PARK |
|---|---|---|
| 1911 | 14500 | 14500 |
| 1915 | | 14460 |
| 1917 | 14350 | 14350 |
| 1922 | 14320[1] | 14350 |
| 1925 | 14320[2] | 14330 |
| 1936 | 14320[3] | 14320 |
| 1944 | 14320 | 14320 |

[1] I. G. Priest in January, 1922, used $c_2 = 14350$ in his work on color temperature.

[2] J. F. Skogland in 1929 used $c_2 = 14330$ in his tables of spectral energy distribution of a blackbody.

[3] D. B. Judd in 1933 used $c_2 = 14350$ in his calculations related to the I.C.I. standard observer.

A critical summary of all the experimental values of $c_2$ was made by Wensel[3] in 1939 in which he arrived at a value of 14360 $\mu°$. However, since the International Temperature Scale is based on the value of $c_2 = 14320$ $\mu°$, it was decided to make no change until after the present emergency. All the values given by Judd[4] in his published work on the 1931 I.C.I. standard observer are based on $c_2 = 14350$ $\mu°$. In Table 4 are given the values of $c_2$ that have been used at the laboratories at Nela Park over the past 35 years, together with the values adopted by Coblentz at various times.

The constant $c_2$ enters into the optical pyrometer calibrations in such a manner that a larger $c_2$ means a smaller value of the temperature above the standard temperature and vice versa.

Formula 4 shows how the value of $c_2$ enters into the calculation for a calibration from one standard temperature, where $R$ is less than unity, or in extending the scale above that of the initial calibration by the use of a rotating section or an absorbing screen. If a different $c_2$ is used the calculated temperature changes as follows:

$$\left[\frac{1}{T_1} - \frac{1}{T_2'}\right] = \frac{c_2}{c_2'}\left[\frac{1}{T_1} - \frac{1}{T_2}\right] \tag{5}$$

where $T_2'$ is the value of $T_2$ corresponding to $c_2'$. The change in $T_2$ due to the use of various values for $c_2$ starting from the melting point of gold, 1336°, is shown in Fig. 2. The change in the higher temperature due to a change in $c_2$ starting from the melting point of palladium can also be obtained from these same curves by differences.

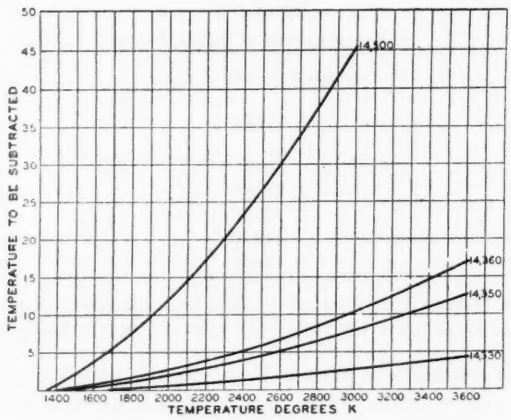


FIG. 2. Change in calculated temperatures due to change in $c_2$ from 14320 for a range of temperatures and a number of values of $c_2$.

## THE INTRODUCTION OF THE DISAPPEARING-FILAMENT OPTICAL PYROMETER

It is not known just when the first optical pyrometer was devised and used; however, sometime in the early nineties the engineers who were connected with the development work on carbon-filament lamps used a carbon incandescent lamp as a disappearing-filament optical pyrometer. These engineers had trouble in setting and resetting the furnaces, used for treating carbon filaments, at the proper temperature to produce the best filament for the lamps they were then making, and so hit upon the plan of using as a comparison source for this purpose the filament of a carbon lamp operating at a certain percentage of its normal voltage and, holding this lamp between the eye and the furnace, setting the furnace at such a temperature that it appeared to have the same brightness as the lamp filament. These settings were purely empirical; the furnace was set by the hit-and-miss process, the criterion being the character of the resulting

heat-treated filaments. The furnace temperature was stated in terms of percent voltage of a lamp of certain watts per candle. After this method had been used for many years, the actual temperatures of the furnaces employed for the different processes were determined by application of some of the new methods. Recently a new lamp[5] has been designed for this purpose which overcomes some of the earlier difficulties. It consists of a bulb (Fig. 3) in which is mounted a sturdy, inverted U-shaped carbon filament, selected for uniformity, and a small eyelet. The filament and background to be measured are viewed through the two openings in the black coating on the bulb. The black coating on the bulb reduces the glare from parts of the background in the vicinity of the area being measured. The small eyelet always appears black against the field and is an aid in selecting the proper part of the filament to use and in keeping the eye focused on the filament when it is about to disappear.

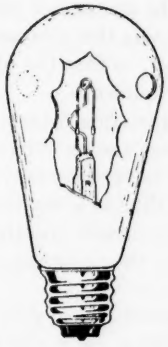

FIG. 3. A pyrometer lamp with bulb cut away to show filament and eyelet

In 1899 Mr. E. F. Morse[6] invented what he called a thermogauge, which consisted of a carbon lamp with a spiral filament in a plane, the lamp being mounted in a tube without any lenses, and one looked through the tube at the source studied and measured its temperature in terms of the voltage applied or the current through the lamp filament when a brightness match was obtained.

An interesting story concerning this pyrometer was told by Mr. J. D. Cox, founder of the Cleveland Twist Drill Company. Mr. Cox said that one time Mr. E. F. Morse ordered from him a number of twist drills and specified they were not to be tempered. These were furnished and no questions asked. When the order was repeated for twist drills with the specification that they were not to be tempered, Mr. Cox asked why they were not to be tempered. Mr. Morse told him that they were not to be tempered because he could temper them better than Mr. Cox was doing. Mr. Cox looked into this and found that Mr. Morse was measuring the temperature of his lead bath, which he used to heat the drills for tempering them, by means of his thermogauge. Mr. Cox finally bought the privilege of using the patented thermogauge for checking temperatures of the

lead bath in which he placed his drills to heat them for tempering. The Cleveland Twist Drill Company is still using, for some of their work on tempering twist drills, this same method of measuring the temperature of the lead baths for heating drills.

Optical pyrometers may be divided into three classes, on the basis of either the method of introducing the comparison source or the method of adjustment used in matching the brightness of the comparison source and the source being studied. The first class has the comparison source to one side and its image reflected into the eyepiece by a mirror or prism at the focus of the objective lens.

In class two, called the polarization type, an image of the source studied and that of the comparison source are observed through the same eyepiece with the light from the two sources polarized in planes at right angles to each other and the balance made by rotating a nicol in the eyepiece.

The third class, called the disappearing-filament type, has as a comparison source a lamp filament, called the pyrometer filament, which is located at the focus of the objective lens. In using this pyrometer, the hot object is seen with the pyrometer filament crossing it, so that the filament appears much the same as the cross-hairs in an ordinary telescope.

There are two types of disappearing-filament optical pyrometers. In the first, and the one most widely used, the photometric balances are made by varying the current through the pyrometer filament. In the second, the filament is kept at a constant current, and thus at a constant brightness, and balances are made by rotating a wedge-shaped circular absorbing screen between the pyrometer lamp and the objective lens, thus varying the apparent brightness of the image of the source studied.

The disappearing-filament type of optical pyrometer of the first type is about the only type of optical pyrometer in use in this country. It is the type that is most convenient to use for the various types of work in the laboratory of the Lamp Department at Nela Park.

This type of pyrometer possesses several advantages over other forms. In the first place, the observer is able to see the object whose temperature is being measured directly through the pyrometer, the same as through a telescope. It is hard to overestimate this advantage. Often it is very desirable to measure the temperature of a particular point of an extended body, as for instance, a particular turn of a coiled lamp filament, a mass of molten iron in the furnace, of a particular spot on an ingot that is being rolled. This can be easily done with this pyrometer while it is very difficult with most other forms. For this reason, this form of pyrometer gives the temperature of a particular small area of the object whose temperature is being measured rather than an average over a more extended area. Also, it is not necessary to have an extended source in order to measure its temperature. Some pyrometers require a source that is very large if the observer is at any distance; such is not the case with this form.

Another advantage that is to be considered is the fact that this form of pyrometer is almost free from any error due to polarization. Any effect due to this cause would be negligible in almost the worst case possible.

## THE LABORATORY FORM OF OPTICAL PYROMETER

A diagram of the arrangement of the different parts of the disappearing-filament optical pyrometer, together with the source being studied—lamp A—is shown in Fig. 4. In the caption are given the dimensions of the various parts of one form of the pyrometer as used in the laboratory at Nela Park. Here, all the different parts are mounted on a substantial optical bench, Fig. 5. Attached to the mounting for the lamp A are extension rods with screw adjustments, so that the observer at the eyepiece F can bring any part of the filament of this lamp in line with the pyrometer filament for measurement. An extension rod is also provided for moving the objective lens to bring the image of the filament of the lamp studied in focus with the pyrometer filament.

With a pyrometer of the dimensions shown, it is possible to measure the brightness of lamp filaments that are as small as about 2 mils (0.051 mm) in diameter. For smaller filaments, a second B & L Tessar lens of about 5 cm

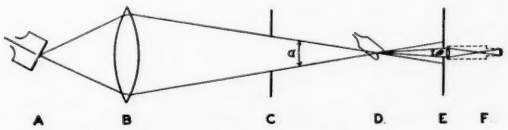


FIG. 4. Diagram showing arrangement of the different parts of the optical pyrometer. A—source studied; B—objective lens; C—entrance cone diaphragm; D—pyrometer filament; E—eyepiece diaphragm; F—eyepiece. The monochromatic filter is located in the eyepiece. As generally used, AB = 35 cm; BD = 120 cm; CD = 50 cm; DE = 30 cm. The lens B is a B&L Tessar about 6.2 cm in diameter with a focal length of about 28 cm. The opening in the diaphragm C is 2 cm in diameter and the opening in the eyepiece diaphragm at E is 6 to 8 mm. To line up the different parts diaphragms with openings about 1 mm in diameter were used at B, C, and E.

diameter and focal length of 22 cm is used with the lens. With this combination, magnification is such that one can measure filaments about as small as 0.5 mil or 0.012 mm in diameter.

A portable type of disappearing-filament optical pyrometer with all the elements mounted in a substantial tube should either have adjustments so that the part of the pyrometer lamp to be matched in brightness against the background image can be brought accurately in line with the center of the optical system of the eyepiece and objective lens or this part of the pyrometer should be accurately mounted in place. The two lenses should either be very accurately centered or means should be provided for centering them in the tube. Many of the difficulties that are to be described in what follows are made much worse if the instrument is not kept in good alignment. The objective lens and the eyepiece lens both should be so mounted that they can be easily and accurately moved to bring the pyrometer filament and the background image into sharp focus, and when they are in the proper focus they should not be easily moved from this position except by intention of the observer. Both of these lenses should be of sufficient quality so that it is possible to get a good image of both the

pyrometer lamp and the source being studied. Since, in general, a so-called monochromatic screen is used in the eyepiece, it is not necessary to have achromatic lenses. However, in order to get lenses that are well enough designed to eliminate other faults of lenses, it may be necessary to use lenses corrected for color also. The size of the lenses used will, of course, depend upon the overall size decided upon for the complete instrument. If the instrument is being constructed for the very accurate measurements necessary for research work, it is well to use the best lens, the best method of mounting, etc., that are available.

In a paper by Fairchild and Hoover,[7] there is given a good description of the type and characteristics of the lens one should use. If the pyrometer is to be used to measure the temperature of sources at low temperature it may be of advantage to use an objective lens of larger light-gathering power so that brightness matches can be more easily made. For very low temperatures it may, of course, be necessary to change the resolving power of the eyepiece to secure good

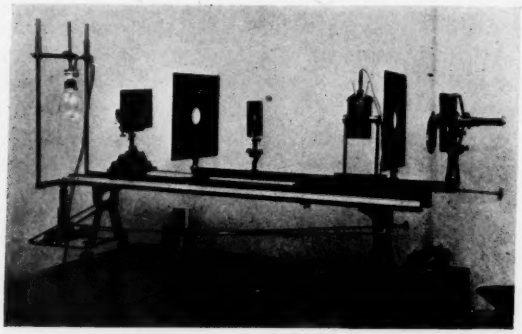

FIG. 5. Laboratory form of optical pyrometer

disappearance if a large objective lens is used. If there are two pieces of red glass in the eyepiece one may be removed, which will give about twice the light. To measure extremely low temperatures sometimes no red glass is used.

### THE PYROMETER LAMP

The pyrometer lamp and its filament are very important parts of this pyrometer. For the most accurate work, the bulb should have plane glass windows on both sides to enable one to obtain the best possible image of a background and the pyrometer filament. These windows should not be perpendicular to the axis of the telescope, but should be at an angle (Fig. 6) of about 15° to 20° from perpendicular, so as to avoid reflecting image and background in view of the field.

A vacuum pyrometer lamp is better than a gas-filled lamp because the relation between the temperature of the filament and the current through it is less affected by the ambient temperature, position of the filament or the housing of the lamp for vacuum lamps than it is in gas-filled lamps. For this use the protection due to the gas is not needed, since very high temperatures—above

1800°K—are not necessary. At first carbon filament lamps were used in the pyrometer, but now tungsten filaments are almost universally used. Tungsten filaments are better than carbon filaments for several reasons. In the first place, tungsten has a longer life at the temperature at which the pyrometer filament is used than a carbon filament. Tungsten also is more uniform in both composition and dimensions than a carbon filament, which gives a more nearly uniform temperature for the tungsten filament. It might be argued that a carbon filament has a larger ratio of current for the same range than a tungsten filament. Some years ago, a test was made of this ratio for both tungsten and carbon pyrometer filaments for the temperature range between the gold point and the platinum point. This ratio of current was very nearly the same with a slight advantage over the carbon filament. Both tests were made for short filaments. For longer filaments, the carbon filament would probably show an advantage over the tungsten filament in this ratio. However, this is unimportant because

FIG. 6. Pyrometer lamp

the current can be measured with sufficient accuracy to overcome any such advantages in either case. The length and diameter of the pyrometer filament are both important.

The tungsten pyrometer filaments are often constructed with a small bend in the filament at the exact point where the filament is to be observed. A small pointer is also sometimes used to help locate the exact point. The 2.5 mil (0.063 mm) filaments require about 0.46 ampere to heat it to such a temperature that it matches in apparent brightness the blackbody at the temperature of melting palladium. If not operated at a brightness above that necessary to match a blackbody at the temperature of melting palladium (1827°K), these filaments will have a long life, and thus maintain their calibration for a long time. A particular pyrometer lamp that had been in use for about two years, and during the greater part of that time had been used almost every day, showed an exceptionally good performance. When it was first calibrated, it required 0.4573 ampere to apparently match the blackbody at the temperature of melting palladium. After about two years of use, for the most part at temperatures in the region 1600–1800°K a calibration showed that it required 0.4578 ampere to apparently match the blackbody at the same temperature. This difference in current corresponds to less than 1°C. As this lamp had been operated about 300 hours in all, it is seen to be very satisfactory.

How accurately the current through the pyrometer filament must be measured

is shown by the following. If the current through the filament is of the order of 0.3 ampere, a change of 0.001 ampere corresponds to a temperature change of about 3°C. Thus, for an accuracy of 1°C, the current will have to be measured to about one part in a thousand.

A battery of sufficient voltage should be used to operate the pyrometer lamp so that a rheostat of large enough resistance can be used to get good control of the current. The rheostat used should be in two parts, the one of large change of resistance per step and the other of small change per step. The resistance per step of the small rheostat should be small enough to give the smallest change in current necessary to set for a brightness match. The entire resistance of the small rheostat should be equal to several steps of the large rheostat. Such an arrangement gives easy operation, and also the operator cannot remember the previous setting.

To measure the current through the pyrometer filament with this high accuracy an ordinary ammeter is not good enough. A special laboratory form of ammeter or some form of potentiometer must be used. If the same potentiometer is used to measure the current through the lamp being studied and the pyrometer, a great deal of time is wasted in changing the potentiometer for each reading. A good method, which is at the same time quite accurate, is to use the deflection potentiometer principle. The regular Leeds and Northrup potentiometer lends itself quite readily to such adaption. By connecting a millivoltmeter or a galvanometer of the proper sensitivity in series with the proper standard resistance and between the binding post marked *Br* and a traveling plug inserted in the proper place on the dial, pyrometer currents can be read to one part in three or four thousand very easily. The readings can thus be made very rapidly and at the end of the set these same readings can be checked on the potentiometer. This makes the current readings practically independent of the constancy of any deflection instrument. With a switch in this millivoltmeter line, the potentiometer is left free to check any other current, such as the one through the lamp that is being investigated.

In what follows it is shown that it is difficult to get good disappearance between the pyrometer filament and the image of the background even for properly selected values of the entrance and exit angle, unless the image of the background is four or five times the size of the pyrometer filament. For measuring the temperature of the small filaments, this dictates a pyrometer filament of not too large a diameter. Another reason for use of filaments of small diameter is that it takes a longer time for the filaments of larger diameter to reach the desired temperature. The end cooling due to the leads is also apt to be more serious for filaments of larger diameter, because, for the same length, they operate at a lower voltage. The length of the pyrometer filaments used in the pyrometer described above is about 4–5 cm. It takes a definite time for a filament of a certain diameter to reach a steady state after the current has been turned on. This time varies about as the diameter of a filament. This time delay, due only to the size of the pyrometer filament, would amount to at most a very few seconds for a filament of any size likely to be used as a pyrometer filament. The

end losses due to the heat conducted away by the leads causes much larger time lags. The length of the pyrometer filament for the above pyrometer was selected to avoid difficulties due to this cause when working with temperatures above about 1800°K. At first a 2 mil (0.051 mm) diameter pyrometer filament was used and later this was changed to a 1.5 mil filament. At 1800°K the effects due to the end losses for a filament of this diameter reach about 1.3 cm from each end, thus the central part of a pyrometer filament 3 to 4 cm in length would be free from such effects. Quite different conditions hold for lower temperatures; that is, for temperatures of from 1000° to 1200°K. For a temperature of 1000°K, the cooling effects due to end conduction for a filament of this diameter (i.e., 1.5 mils) reaches about 4 cm from the leads. Another cause of trouble at these lower temperatures is the effects due to changes in the ambient temperature. A pyrometer lamp that may be quite satisfactory at high temperatures may have its calibration completely changed at low temperatures by a change in the ambient temperature. Dr. Wensel[3] of the National Bureau of Standard made a test of the effect end losses and the ambient temperature have on the time lag for a pyrometer filament about 3 mils (0.076 mm) in diameter and about 3 cm in length. This filament required a current of about 0.33 amperes to heat it to 1000°K. For this temperature the cooling due to the end effects extends somewhat over 5 cm from each lead. Thus no part of this filament can be said to be at the temperature corresponding to the current through it for a long filament. For this test Dr. Wensel had a second pyrometer lamp constructed with wire of the same size, but having the total filament length of 10 cm. This extra length was obtained by coiling the filament at each end, thus enabling this longer filament to be mounted in a bulb of the same size as that used for the filament 3 cm long. While it required 0.33 amperes to heat the short filament to 1000°K, it required only 0.18 amperes to heat this longer filament to the same temperature. For a temperature of about 1700°K, where the effects due to conduction extend only about 1.5 cm from each end for this size filament, both lamps required the same current. If the pyrometer lamp with a 3 cm filament were heated to about 1200°K and the current changed to a value to give 1000°K, it took about four minutes for the middle of this filament to reach within 1° of its final value. For the longer filament, the time required for the corresponding change in temperature required only 10 to 20 seconds. It was found that the current necessary to heat this short filament to a temperature in the neighborhood of 1000°K was a function of ambient temperature. For this temperature, i.e., 1000°K, a 1° change in the ambient temperature produced about 3° change in the temperature for constant current, i.e., about 0.33 amperes for the short filament; and the change in temperature of the long filament with the current also constant, i.e., about 0.18 amperes, for this change in ambient temperature, could not be measured. Both this long time lag and effect of the ambient temperature are caused by the temperature change due to the conduction of heat away from the filament by the leads. Thus, for accurate results at these low temperatures, the cross section and length of the filament should be so chosen as to overcome, at least in part, the effect of the lead losses.

## CARE OF THE OPTICAL PYROMETER

The optical pyrometer is an optical instrument and should be treated and handled as such. The lenses and lamp windows should be kept clean, but in cleaning them it must be remembered that these are optical surfaces and care should be exercised in cleaning them so as not to scratch the glass. The glass parts between the pyrometer filament and the source measured can become so covered with dirt as to alter seriously the calibration. A clean piece of glass transmits about 90 percent of the direct radiation, but it would not have to become very dirty to transmit only 85 percent of the direct radiation. This change in transmission would cause an error of about 11°C at a temperature of 2000°K.

Users of the pyrometer must see to it that it gets no hard knocks, such as would result from dropping it on the floor, as this might throw some part out of alignment, which might cause serious error in calibration. The current-measuring device for portable pyrometers also must be carefully handled if it is to be reliable for its intended use.

Several different forms of the disappearing-filament optical pyrometer have been offered to the public by various instrument makers. The authors of this paper are familiar with only two types thus offered. About twenty-five years ago Leeds & Northrup put out a form of the pyrometer that was good, but left something to be desired. About ten years ago these same apparatus manufacturers brought out an improved form of this pyrometer that is very good, very easy to use, and gives good results in measuring temperatures. They use a small tungsten ribbon as the pyrometer filament and measure the current through the filament with a sort of a potentiometer device that enables accurate results to be obtained.

## THE OPTICAL PYROMETER AS A TELESCOPE

The disappearing-filament optical pyrometer is basically a telescope and thus the precautions necessary for the use of a telescope as an optical instrument must be observed. The telescope must, in general, produce a magnified image of the source observed. This image is said to be true when it is (1) sharply defined and (2) undistorted. How nearly these results are obtained depend upon the character of the lenses used and how well they are mounted.

The brightness of a luminous surface as observed directly by the eye is independent of the distance from the eye, and no optical instrument can increase this observed brightness. The highest observed value for the brightness of a luminous surface that can be obtained with a telescope is that obtained by direct eye observation reduced by the absorption, scattering and reflection of the optical parts of the telescope. This holds for magnification up to the value where the pupil of the eye is just filled by the final cone from the telescope. A greater magnification reduces the observed brightness. Since the opening of the pupil of the eye is variable, there must be a fixed diaphragm to limit the final cone to a value somewhat less than that of the pupil. This insures a definite value of observed brightness for any balance point and in what follows this

fixed limiting diaphragm in the eyepiece is shown to be necessary for other reasons. This one limiting diaphragm is sufficient to insure that the brightness of the object observed through a pyrometer does not vary with its distance or magnification, so long as this diaphragm is filled with light from the source studied. The pyrometer lamp filament is placed at the focus of the objective lens and thus it is seen through the eyepiece projected across the image of the object observed. A balance with this type of optical pyrometer consists in varying the current through the pyrometer filament until it apparently matches in brightness the image of the luminous surface on which it is seen projected. At first thought, one would be apt to say that a match could always be obtained under any fixed condition of the optics of the telescope, and that the brightness of the pyrometer filament and the image of the background were the same when they appeared to be matched in brightness. Such is not always the case.

There have been two papers published on the relation between the brightness of the pyrometer lamp and the background image. The one paper was written by one of the present writers and A. G. Worthing[9] and the other by Fairchild and Hoover[7] at National Bureau of Standards. In the main, these two papers are in agreement, but there are some points of difference.

## CONDITIONS FOR DISAPPEARANCE OF THE PYROMETER FILAMENT

There are three reasons why an exact brightness match is not always possible and why the pyrometer filament and the background image are not always at the same brightness when they are apparently matched in brightness.

The first is the departure of the radiation from a tungsten filament from Lambert's Cosine Law of Radiation. This law of radiation is a statement of the fact that the brightness of a blackbody is independent of the direction from which it is observed. Such is, in general, not the case for other radiators such as the tungsten filament. Worthing[10] has shown that the relative brightness across a heated round tungsten filament varies as shown in the curve in Fig. 7. Thus, due to this cause alone, the center of the pyrometer filament is about 15 percent less bright than it is near the edges. This difference in brightness can be seen under proper conditions if one uses sufficient resolving power in the eyepiece of the telescope and may seriously interfere with obtaining brightness matches.

Another cause for the non-balance and for differences in the brightness of the pyrometer filament and background image when they are apparently matched is the diffraction that takes place at the edge of the pyrometer filament even when it is at the focus, as is the case here. This diffraction can be shown by mounting a razor blade at the focus of the objective lens; i.e., in the position of the pyrometer filament.

A third source of trouble is the reflection of light from the edge of the round filament. An apparent brightness match can occur only when in some way the three above causes overlap and when one uses an eyepiece of small enough resolving power that these different effects cannot be resolved. This may or may not give conditions of equal brightness of the pyrometer filament and the background image when they are apparently at the same brightness.

The characteristics of the lenses and other glass in the path may greatly affect the reflection and diffraction at the pyrometer filament. The best conditions are obtained when one uses high-grade lenses and flat windows for the pyrometer lamp. Also, it is necessary to have the different parts very accurately in line, as is the case for any telescope for the best results.

With three such different effects to interfere with equality of brightness between that of pyrometer filament and the image of the background, the wonder is that good disappearance can be obtained at all. Set-ups have been experimented with, as described in what follows, where different types of filaments have been used and that, too, with such conditions of disappearance that dark or bright edges of the pyrometer could not be seen. If good disappearance and reproducibility of results are what is meant by proper disappearance, the ratio of the brightness of the filament and the image are not always unity under such conditions.

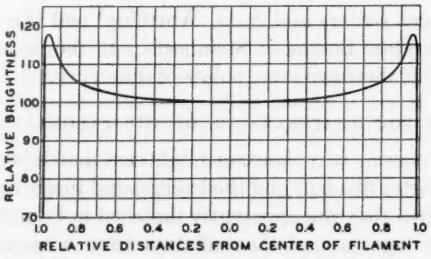


FIG. 7. Relative brightness across a round tungsten filament. Observations made perpendicular to axis of filament.

To say that the usefulness of this form of the instrument is considerably restricted if the pyrometer is so set up and so used that all of these effects at the pyrometer so combine as to result in a difference in relative brightness between the pyrometer filament and the image of the source being tested, when they are apparently matched, seems to miss the point for an instrument of this kind. The optical pyrometer is in reality a "transfer instrument" and as such it must be calibrated under the same conditions as those under which it is to be used. When so calibrated and so used, it should give in the hands of different observers the precision needed for the purpose at hand.

The tests and uses made of the disappearing-filament optical pyrometer in this laboratory show that considerable variation in this ratio is not incompatible with high accuracy in the measurement of surface brightnesses with an optical pyrometer. The necessary and sufficient condition for accurate operation of this pyrometer is that it must be so constructed and used that the relation between the current through the pyrometer filament (which is a measure of its brightness) and the brightness of the source sighted upon should remain constant for the range of conditions under which the pyrometer is used.

In the paper already referred to[9], conditions of construction and use of this pyrometer are set up for avoiding all errors due to these various effects happening at the pyrometer filament. Although the work upon which this paper is based is now about thirty years old, the same conditions are still used in the standard pyrometer described in this paper. These conditions are in no manner serious limitations of the use of this optical pyrometer. As shown by Fairchild and Hoover[7], conditions can be found that give equality of brightness between the pyrometer filament and the image of the source studied, but one can make and use a pyrometer without following the conditions necessary for the pyrometer filament and the image of the background to be equal in brightness.

In the first of the two papers already mentioned[9], Worthing and Forsythe, working with very small values of the angles $\alpha$ and $\beta$, Fig. 4, studied the relative brightness of the pyrometer lamp and background image and showed that the ratio of these brightnesses depended upon the size of the pyrometer filament and the values of the entrance angle $\alpha$ for a fixed exit angle $\beta$. Four sizes of tungsten pyrometer filaments were used, having diameters 0.016, 0.025, 0.05, and 0.10 mm respectively, and the value of the relative brightness of the pyrometer filament to that of the background image measured for entrance angles, ranging from 0.0055 to 0.022 radian for an exit angle of 0.005 radian. A reference to Fig. 4 will show that the light from the background lamp A must pass through one thickness of its own bulb, the lens B, and one thickness of the bulb of the pyrometer lamp D before its image is matched in brightness with this pyrometer filament. The transmissions of these parts were measured and the brightness of the filament of the background lamp A corrected by these values before it was compared with the brightness of the pyrometer filament. This study was for red light ($\lambda = 0.665\ \mu$). Some studies were made for a carbon pyrometer filament and for blue light ($\lambda = 0.467\ \mu$).

All of these data on the tungsten pyrometer filament using red light have been assembled on one curve by plotting the relative brightness of the pyrometer filament and the background image against the product of the entrance angle $\alpha$ and the pyrometer filament diameter D. The agreement shown in Fig. 8 would seem to indicate that the primary cause of the variation in brightness found was diffraction, since the amount of light diffracted into the shadow varies rapidly with the diameter of the filament for the small angles used in this test, while the light reflected from the pyrometer filament would vary about as the diameter of the filament and the angle and the variation of Lambert's Cosine Law would not vary with the diameter.

It is to be noted that the relative brightness approaches the value of 90 percent. That is, it was found that, for these conditions, the brightness of the pyrometer filament was only 90 percent of that of the background image in the same plane for an apparent brightness match.

Several times since the above data were taken, the relative brightness of the pyrometer lamp and the background image was measured for the pyrometer, Fig. 4, as set up for use in the regular laboratory work. This was for an entrance

angle of 0.037 radian and for an exit angle of 0.02 radian, using a pyrometer lamp with a filament about 0.045 mm in diameter. The ratio of these brightnesses found in each instance was in the neighborhood of 90 percent.

During the preparation of this paper, a double pyrometer similar to one used in the earlier work was set up by mounting a second B. & L. Tessar lens in line with the lens, B, Fig. 4. This second lens has a diameter of about 5 cm and a focal length of about 22 cm. By the use of this lens, the image of a second background lamp could be thrown in the plane of the background lamp shown at A. The brightness of the image of this second background and the brightness of the second pyrometer lamp placed in the position of the first background lamp at A could be directly compared by use of the first pyrometer lamp located at D without making any corrections for the transmissions of the lens or the lamp bulbs.

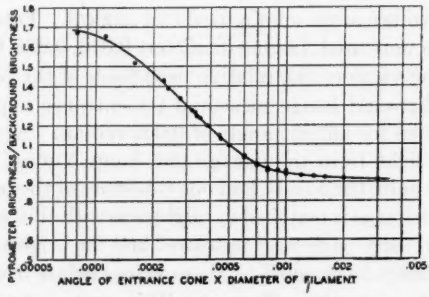


FIG. 8. Ratio of brightness of pyrometer filament to that of image of background filament, as a function of αD, the product of the angle of the entrance cone in radians and the diameter of the pyrometer filament in mm, for a constant exit cone of .005 radian. Allowance up to 10% has been made for differences between the nominal and actual diameters of the various pyrometer filaments.

The second background was a tungsten ribbon filament 3 mm wide and its image was focused in the plane of the first background—the pyrometer filament to be tested—with the second lens so located that the entrance angle was about 0.16 radian. Several different pyrometer filaments were used as the first background and their brightness compared with that of the image of the second background. The results are given in Table 5. They show that, with the entrance and exit angles used, the brightness of the various pyrometer filaments, when operated separately at the currents which had given an apparent match with the background lamp, were not the same as that of the image of the background lamp. With the pyrometer shown in Fig. 4 a 10 mil (0.25 mm) were filament and a 1 mm ribbon were used as the pyrometer filament and matched against the background, which consisted of a 3 mm ribbon filament. The value of the entrance angle used was 0.10 radian, with an exit angle of about 0.027 radian. Later the relative brightness of the 10 mil wire and 1 mm ribbon filament were measured with the regular pyrometer and it was found that the

wire filament was only 90 percent as bright as the ribbon when each was heated with the current necessary for a match with the background image in brightness.

The regular Leeds & Northrup optical-pyrometer lens was used as the second lens of the double pyrometer, and the Leeds & Northrup pyrometer filament compared in brightness with the 3 mm ribbon. In this case the entrance angle was somewhat smaller than is regularly used with the Leeds & Northrup pyrometer. Here the brightness of the pyrometer filament was only about 90 percent that of the image of the 3 mm ribbon.

TABLE 5

*Results of some tests on the relative brightness of pyrometer filament to background image using a double pyrometer*

| TEST | ENTRANCE APERTURE | EXIT APERTURE[1] | | FILAMENT TESTED | RELATIVE BRIGHTNESS[2] |
|---|---|---|---|---|---|
| | | 1 | 2 | | |
| 1 | 0.16 | 0.033 | 0.023 | 0.25 mm wire | 0.87 |
| 2 | 0.16 | 0.023 | 0.023 | 0.24 mm ribbon | 0.90 |
| 3 | 0.16 | 0.02 & 0.03 | 0.023 | 0.045 wire | 0.93 0.88 |
| 4 | 0.16 | 0.04 & 0.027 | 0.027 | 0.5 mm ribbon | 0.97 (0.97) |
| 5 | 0.16 | 0.02 & 0.03 | 0.023 | 0.03 mm ribbon | 0.95 0.94 |
| | | | | | Pyrometer Current |
| 6[3] | 0.04 | | 0.02 | 0.045 mm wire | 0.2765 |
| | 0.05 | | 0.02 | 0.045 mm wire | 0.2765 |
| | 0.07 | | 0.02 | 0.045 mm wire | 0.2760 |
| | 0.10 | | 0.02 | 0.045 mm wire | 0.2746 |

[1] Exit aperture No. 1 was used in matching the filament tested with background No. 2. Exit aperture No. 2 was used in measuring the relative brightness of the filament tested and the image of background No. 2.

[2] The values given in column 6 are the relation of the filament tested to that of the image of background No. 2. The three relative brightnesses given in column 7 are for these three filaments, set at the currents they required to match the brightness of the second background, with the double pyrometer, as later measured with a large magnification.

[3] This test was made with the regular pyrometer measuring the 0.17 mm diameter filament, of the standard of temperature, for the different entrance angles $\alpha$ shown in column 2. It is to be noted that the required pyrometer current for apparent brightness match decreased as the entrance angle was increased. This difference in current through the pyrometer lamp corresponds to about 4% difference in brightness.

It is very difficult to compare the brightness of the pyrometer filament and the image of the filament studied unless the image is much wider than the diameter of the pyrometer filament. If the image is not about four times as wide as the diameter of the pyrometer filament, dark edges will appear along the edge of the pyrometer filament. When it is necessary to measure the temperature of a lamp filament of small diameter; i.e., much less than 2 mils (0.052 mm), with this pyrometer, a second lens is mounted near the lens B of such a focal length that the magnification due to the pyrometer is about doubled. In this way it is possible to measure the brightness of a filament of a very small diameter; e.g.,

about 0.6 mils (0.015 mm), using a pyrometer filament that is about 1.5 mils (0.038 mm) in diameter.

An experiment was made to find out how well one could make matches between a pyrometer filament and a background when the two were about the same size. A regular pyrometer filament (0.038 mm in diameter) was used as a background image and matched with its image crossing that of the pyrometer filaments, both with the background horizontal and the background making an angle of 45° with the horizontal. There was not much difference found when measuring the temperature of a 1.5 mil filament with a one to one magnification with the two images crossed than when using a larger magnification. The range in the reading, however, was much greater with the smaller images.

Benford[11] made a suggestion that if it were necessary to measure the temperature of a small filament with a large pyrometer filament, more consistent results could be obtained if the corssed images were so adjusted that each made an angle of 45° of the horizontal than when one of them was horizontal. It was his opinion that this was related to the habit of the eye in moving along a line when reading. This was tried out, using the Leeds & Northrup optical pyrometer. Benford's idea was not altogether substantiated. Two observers made this test and one of them felt there was no difference in the ability to read under the two conditions, and the second observer seemed to do somewhat better when the two images were at 45°. The readings of the first observer were 15°F (8°K) lower than the correct temperature of the filament investigated, and the readings of the second observer were about 14°F (8°K) higher.

This difficulty of making brightness matches unless the image is wider than the filament was tested, in a way, by mounting a slit at the position of the first background and measuring the brightness of the 3 mm ribbon filament as seen through the slit set at various openings. Good disappearance was found down to slit widths of 0.2 mm when using the regular pyrometer filament 0.038 in diameter for an exit angle of 0.027 radian, and down to about 0.1 mm slit widths for an angle of 0.02 radian, although the lens used gave a magnification of about 3×. Of course, one would expect some trouble due to interference at the edge of the slit, but it must be noted that the disappearance failure was due to dark edges along the pyrometer filament.

The filament tested has been used as the pyrometer filament in some work because it was thought that the brightness of a smaller filament could be thus measured. There may be conditions where one would find it necessary to use the filament tested as the pyrometer filament, but if lenses of a proper magnification are available this is not necessary. Many lamps that have to be measured have filaments of very small diameters with the filament in such form and so mounted that it would be practically impossible to make any study of the surface brightness or temperature by mounting them as pyrometer filaments. It is much more satisfactory to use the pyrometer filament as a transfer instrument, and use a set up with sufficient magnification to enable the surface brightness of the tested filament to be measured directly.

The errors in temperature introduced due to poor disappearance are small especially as the substitution method is generally used. Poor disappearance caused by dark or bright lines along the pyrometer filament interferes greatly with the consistency of making brightness matches.

Several other very interesting phenomena were observed with the pyrometer, but there was neither time nor equipment available for their study.

## MONOCHROMATIC SCREEN

A reading with this optical pyrometer consists in a brightness match with the pyrometer filament and the image of the source across which it is seen projected. Such brightness matches can be made using the total visible spectrum, but if this is done, errors are apt to be introduced and observers may differ widely in their readings, even for the slight color difference found when matching a tungsten pyrometer filament against a blackbody, because the tungsten filament radiates in such a manner that for the same brightness it gives a bluer light than that of the blackbody when they are at a brightness match. This difficulty can be overcome and a much more accurate brightness match made by using a so-called monochromatic screen or some prism device in the eyepiece of the pyrometer to restrict the wavelength range.

An optical pyrometer can be so calibrated and so used as to make unnecessary a knowledge of the wavelength selected by the prism or of the extent to which the screen is monochromatic. To do this requires a blackbody furnace that can be operated at various temperatures up to the highest temperature for which the pyrometer is to be used. It is not always possible to operate a blackbody for this range of temperatures and be sure that the temperatures are accurately known. Thus it may be necessary to calculate the temperature of a blackbody whose brightness has some ratio, say, ten times that of another blackbody at some standard temperature. To use Wien's formula to calculate temperatures from relative brightness measurements; that is, to find the temperature of a blackbody having a brightness of ten times (or one-tenth assuming a sector or absorbing glass transmission of one-tenth) that of a blackbody whose temperature can be measured directly, a knowledge of what wavelength to use is necessary; also, the wavelength must be known if the pyrometer is used to measure the temperature of non-blackbodies.

## SPECTROPYROMETER

The use of a prism to limit the wavelength gives what has been called a spectropyrometer. If for any reason it is desired to study brightnesses for any selected wavelength region it may be necessary to use such a spectropyrometer. A diagram of one form of this instrument is shown in Fig. 9. This spectropyrometer is built around a constant deviation spectrometer as shown.

The pyrometer filament, located at H, Fig. 9, is a two mil tungsten wire and is so mounted that its image, formed across the slit of the spectrometer by the lens at F, is horizontal, while the slit is vertical. The background lamp or other

source studied is so mounted that its image at the slit is vertical, and of such width as to much more than cover the slit. To obtain a good brightness match of the image of this pyrometer lamp with the background it was found necessary to have all the different parts well lined up, and also to use a diaphragm with a small opening at G for the more luminous parts of the spectrum. The opening in this diaphragm could be made larger for work at the ends of the spectrum, where the amount of light was much less. The image of the pyrometer filament, as seen through the eyepiece, has to be carefully focused for accurate work. As this depends somewhat upon the wavelength used, a scale is attached to the lens at F, so that it is possible to reset this at the proper place for the different parts of the spectrum after it had once been calibrated.

A very definite and known wavelength is generally given by the spectrometer part of the spectropyrometer. This enables the temperature to be calculated from the measured brightness values, using Wien's equation. To insure this

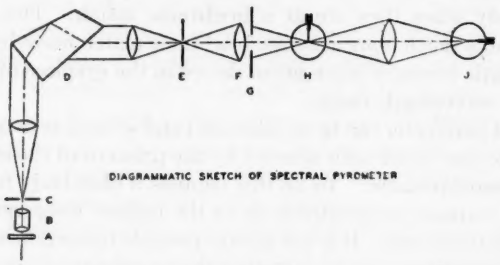


FIG. 9. Spectral Pyrometer

condition, however, care must be given to the width of the spectrometer slits as related to the dispersion of the prism used, since the prism can be so mounted and so used as to transmit a band of energy of a wide range of wavelengths.

## EFFECTIVE WAVELENGTH OF "MONOCHROMATIC" SCREEN

For most of the work a good monochromatic screen in the eyepiece of the optical pyrometer is the most satisfactory method of limiting the wavelength interval used. An optical pyrometer with a special red glass filter as the monochromatic screen was calibrated[12] from a blackbody held at the palladium point by the method to be described in what follows. This calibration was extended to a temperature lower than the gold point, and it was found that the calibration thus obtained for the gold point did not check that obtained from the blackbody held at the gold point. An investigation showed that this error was due to two causes, one being the use of the wrong value for the wavelength of the red glass filter.

A study was made of the wavelength that should be used for the monochromatic screen with the net result that one serious source of error was removed from optical pyrometry. This study showed that when a monochromatic screen

is used under the conditions that require a knowledge of the wavelength used, some consideration is necessary and this led to the following definition of this wavelength called the "effective wavelength."

In using the pyrometer, it is the integral brightnesses through the monochromatic screen that are compared, for which reason the effective wavelength[12] of the monochromatic filter for a certain temperature interval has been defined as the wavelength for which the ratio of the intensities of blackbody radiation for any two temperatures, calculated by using the Wien formula, and this wavelength is the same as the ratio of the measured brightnesses of a blackbody for the same two temperatures using the filter in question in the eyepiece of the pyrometer. If the effective wavelength of the screen used is known just as accurate results can be obtained by calculation and the screen will, in general, transmit more light, permitting better settings to be made for brightness matches at low temperatures.

A so-called monochromatic screen of almost any color desired may be obtained and used in the eyepiece of the pyrometer. Work has been done with a red, a blue, a green, or a yellow-green screen in the eyepiece of the pyrometer for some special investigations. For the most part, however, red glass screens have been used for the following reasons: (1) at low temperatures, the red radiation first becomes visible and thus readings may be made at a somewhat lower temperature with the red glass; (2) the color change for a change in wavelength is much less in the red part of the spectrum than in the green, which makes the red the better part of the spectrum for this work; (3) better monochromatism can be obtained in glass of this color; (4) by using a red screen when measuring a temperature so high that a rotating sector or absorbing glass is necessary, the transmission of the sector or absorbing glass that must be used to reach a particular temperature is greater for the longer wavelength than it is for the shorter wavelength. The definition of the effective wavelength can easily be expressed by a formula. This formula, from which $\lambda_e$ can be calculated for the temperature interval $T_1$ to $T_2$ is as follows:

$$\frac{\int J(\lambda T_1) K_\lambda \tau_R \, d\lambda}{\int J(\lambda T_2) K_\lambda \tau_R \, d\lambda} = \left[\frac{J(\lambda T_1)}{J(\lambda T_2)}\right]_{\lambda_e} \tag{6}$$

where $J(\lambda T)d\lambda$ is the energy, as given in Wien's equation or formula for the wavelength interval from $\lambda$ to $\lambda + d\lambda$; $\tau_R$ is the spectral transmission of the red glass; and $K_\lambda$ is the luminosity; and thus the integral indicated by the numerator of the part of this formula to the left of the equal sign is the brightness of the blackbody at temperature $T_1$ (the denominator the brightness for temperature $T_2$) as seen through the red screen in the eyepiece of the pyrometer. These integrals can be computed by the step-by-step method with sufficient accuracy for this purpose.

In Fig. 10 are shown the spectral transmissions of several red glasses that are nearly enough monochromatic for use under various conditions. The glass having the spectral transmission shown by curve A does very well for a commercial pyrometer for low temperature ranges because it transmits so much light.

The glasses having the transmission shown by curves B, C, and D are suitable for the most accurate work.

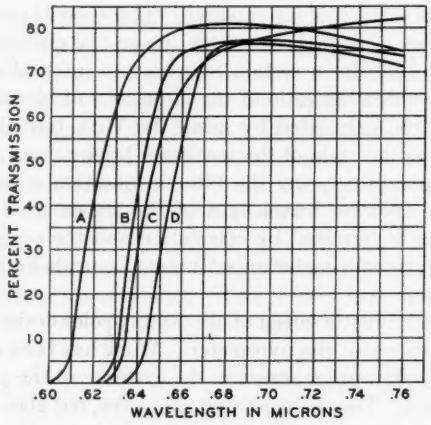


FIG. 10. Spectral transmission of various red glasses. Curve A—for Corning high-transmission red, marked 150 percent, 5 mm thick. Curve B—for Corning high-transmission red, marked 50 percent, 5 mm. thick. Curve C—for Jena red 4512, 2.93 mm thick. Curve D—for Corning high-transmission red, marked 28 percent, 6 mm thick.

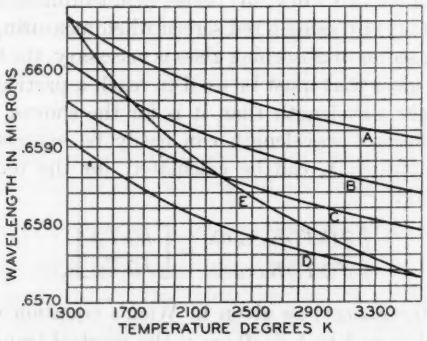


FIG. 11. Effective wavelengths for Corning red glass. Spectral transmission shown by Curve B, Fig. 10. Curve A: effective wavelengths from 1300° to other temperatures. Curve B: effective wavelengths from 1800° to other temperatures. Curve C: effective wavelengths from 2400° to other temperatures. Curve D: effective wavelengths from 3600° to other temperatures. Curve E: limiting effective wavelength.

Using formula 6, the effective wavelength was calculated for the red glass having the spectral transmission shown by curve B, Fig. 10, for a number of temperature intervals and plotted as shown in Fig. 11. By connecting the points where the curve for the effective wavelength from any particular temperature crosses the same temperature ordinate, a curve is obtained (E, Fig. 11) that gives the limiting effective wavelength for a particular temperature.

To show how these curves may be used, the effective wavelength for a couple of temperature intervals will be found. The effective wavelength between 1800°K and 2900°K is given by the ordinate of the point where the 1800°K curve crosses the 2900°K ordinate; that is, it is 0.6587 $\mu$. For the range between 2100°K and 2900°K, the effective wavelength is likewise given by the point where the 2100°K curve would cross the 2900°K ordinate. The 2100°K curve is not drawn, but will have to be imagined as being parallel to the 1800°K, one point of its position being determined by where the curve E crosses the 2100°K ordinate. The effective wavelength for this interval is 0.6584 $\mu$. It can be seen from the figure that the effective wavelength for any temperature interval is given quite closely by the mean of the limiting effective wavelengths for the two temperatures.

To determine the effective wavelength for a particular red glass requires considerable work both in determining the spectral transmission and in calculating the final values. To determine the effective wavelength for every glass used in optical pyrometers would be laborious. It is fortunately possible to obtain the effective wavelength of an unknown piece of glass in terms of a standard red glass with very few measurements.

If the relative brightness of a blackbody for two temperatures is measured both with the standard red glass and the glass being investigated, it is possible to compute the effective wavelength of the unknown glass from that of the standard red glass and the ratios of the blackbody brightness thus found. From the definition of the effective wavelength and Wien's equation, the following formula is found connecting the effective wavelength and the ratio of the blackbody brightness:

$$\frac{(\lambda_e)_a}{(\lambda_e)_x} = \frac{\log B_x}{\log B_a} \tag{7}$$

where $(\lambda_e)_a$ and $(\lambda_e)_x$ are the effective wavelengths for the glasses $a$ and $x$ for the range studied, and $B_a$ and $B_x$ the ratio of the brightness of the blackbody for the two temperatures for red glasses $a$ and $x$.

The effective wavelength of two monochromatic screens can be compared using a tungsten filament as the source in place of the blackbody. The tungsten filament does not show the same increase in brightness[18] for the range betwen color temperatures $T_{c_1}$ and $T_{c_2}$ as does a blackbody for the same range of temperature. This difference is quite small and for most work would be negligible, but for the highest accuracy it must be taken into account. If the brightness of a tungsten filament is measured between the two color temperatures $T_{c_1}$ and $T_{c_2}$, for both the standard and the unknown glass, the effective wavelength for the unknown glass can be calculated accurately by means of the equation:

$$\log\left(\frac{B_a}{B_x}\right) = c_2 \log e \left[\frac{1}{(\lambda_e)_x} - \frac{1}{(\lambda_e)_a}\right]\left[\frac{1}{T_{c_1}} - \frac{1}{T_{c_2}}\right] \tag{8}$$

Because the ratio for tungsten is only slightly different from the like ratio for a blackbody between the same color temperature, equation 6, with but a slight error, may be reduced to equation 7.

Experimentally it has been shown that if the effective wavelengths are determined for two red glasses that have somewhat the same spectral transmission, the relation between the effective wavelength is given quite approximately by the relation:

$$(\lambda_e)_a = (\lambda_e)_x + \text{constant} \tag{9}$$

This formula holds for the glasses investigated to all the accuracy needed for temperature measurements.

Formula (4) shows how the effective wavelength of the red glass used enters into the calculation of the temperatures extrapolated from a standard lamp. The results of some calculations given in Table 6 show what errors may arise from the use of the wrong $\lambda_e$ in these calculations. These results show the necessity for using the proper effective wavelength.

TABLE 6

*Errors in extrapolated temperatures due to an error in the effective wavelength*

| TEMPERATURE EXTRAPOLATED FROM 1827°K | CORRECT EFFECTIVE WAVELENGTH | ERROR DUE TO USING WRONG EFFECTIVE WAVELENGTH | |
|---|---|---|---|
| | | A* | B** |
| 1000°K | 0.6675$\mu$ | +0.8 | −4.5 |
| 1336 | 0.6664 | 0.0 | −3.6 |
| 1600 | 0.6657 | −0.2 | −2.0 |
| 2000 | 0.6651 | +0.3 | +2.0 |
| 2500 | 0.6647 | +2.4 | +9.1 |
| 3000 | 0.6645 | +5.5 | +19.2 |

* A—using effective wavelength for interval between 1336 and 1827°K.
** B—using effective wavelength that is 1% too large.

EFFECT OF CHANGE OF TEMPERATURE OF RED GLASS ON ITS SPECTRAL TRANSMISSION

In connection with the investigation of the effective wavelengths it was observed that the transmission of the red pyrometer glass, presumably dependent for the color on a colloidal solution, is subject to a large change with temperature[12]. This has not been investigated thoroughly, but observations were made at two temperatures, 20° and 80°C, by immersing the glass in water heated to these temperatures. The results are given in Fig. 12. Curve A is the transmission of the glass at the lower temperature, 20°C, and curve B the corresponding curve at the higher temperature, 80°C. The transmission is shown to decrease with increase in temperature, the coefficient of change of temperature being greatest in the shorter wavelengths. The change is such as to make the transmission band appear to shift to longer wavelengths as the temperature is increased.

A test was made of the effect of this temperature shift of the transmission band on temperature measurements when the red glass was used as a screen before the eyepiece of the pyrometer. The temperature of a broad carbon filament lamp operated at a brightness temperature of 1900°K was measured

with the red glass at room temperature (20°C) and at 80°C using a sectored disk with a 2° opening, since this would give a larger effect than a sector with greater transmission. It was found that there was a decrease of about 5°C in the temperature obtained when the glass was heated to 80°C over that obtained with the glass at room temperature. This shows that, for all ordinary temperature changes, the effect is negligible.

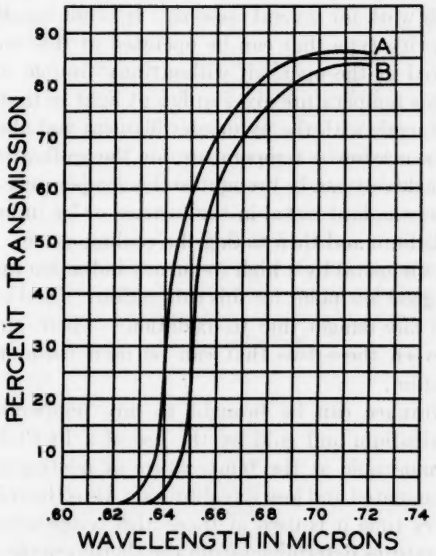


FIG. 12. Spectral transmission of a single thickness of glass F-4512; A at 20°C; B at 80°C.

## CALIBRATION OF OPTICAL PYROMETERS

Questions are often asked concerning the starting point for the calibration of the optical pyrometer. To make a completely independent calibration of any pyrometer would be a great undertaking. Fortunately, this is not often necessary or desirable.

The calibration of a disappearing-filament optical pyrometer consists of the relation between the current through the filament and the temperature of the blackbody against which the pyrometer filament has been matched in brightness by eye observations through the eyepiece of the pyrometer. In the region above 1200°K, the region generally covered by the optical pyrometer, there are two difficulties. The first is the necessity of reaching this high temperature in such a way that it can be controlled and measured, and, in addition, there is the second difficulty of getting and maintaining the blackbody conditions, since temperature in this region depends upon the radiation laws of the blackbody.

The direct way to calibrate the pyrometer is to have a blackbody that can be operated at various known temperatures over the entire range that it is desired

to use the pyrometer. This is always very difficult and sometimes impossible. The main trouble is to get a blackbody that will stand the high temperatures, and at the same time it is difficult to get a satifactory method of measuring these temperatures. Not all standard blackbodies can be operated at a temperature higher than that of melting palladium (1827°K).

A blackbody can be brought to a definite temperature by the use of standard melting point metals. The palladium point (1827°K) is a very satisfactory temperature for such work for several reasons. It is not too difficult to build a blackbody of the cavity type that can be operated at this temperature. Palladium can be melted in the open air without any trouble due to oxidation. The blackbody at this temperature gives sufficient light so that accurate brightness matches can be made with the pyrometer filament and also, in general, this makes a satisfactory maximum temperature for the calibration of the optical pyrometer. The blackbody can be brought to this temperature either by melting small samples of the standard metal in the furnace or by immersing the blackbody in molten palladium and then taking the cooling curve. This can readily be done by melting the metal by a high frequency induction furnace. The gold point (1336°K) is a good low point for this calibration. Gold can also be melted in the open without any danger due to oxidation. There are no metals with melting points between these two that can be used without a great deal of trouble due to oxidation.

The blackbody furnace can be brought to any temperature between the melting point of palladium and gold by the use of a Pt-Pt-Rh thermocouple. However, this thermocouple at the temperature of melting palladium is very apt to become contaminated and lose its calibration, thus the calibration has to be checked almost every time it is used at these high temperatures and, also, the intermediate temperatures determined from the thermocouple calibration might be in question. Thus some other method of calibrating the pyrometer is necessary.

An optical pyrometer can be calibrated from a blackbody held at a particular temperature[14]. Since the blackbody thus used is to be the standard of reference, a standard temperature, that is, one determined by means of a standard melting point is generally chosen. A very good temperature for such work is that of melting palladium, or the palladium point. There are three reasons for the choice of this point. In the first place, it is about as high a temperature as a platinum-wound furnace can be operated. In the second place, this temperature is about as high as the pyrometer filament will stand if it is to have a long life. In the third place, the temperature of melting palladium is very well known in terms of the laws of radiation and the temperature of melting gold.

The standard radiator at the standard temperature gives one point on the calibration. The entire calibration of the pyrometer can be obtained from the blackbody at this standard temperature if some means, such as a rotating sectored disks (to be described below) or absorbing glasses of known transmission for reducing the apparent brightness of the incident radiation, are available. If readings are made of the current through the pyrometer filament for an

apparent brightness match with a rotating sector or an absorbing glass of known transmission between the pyrometer lamp and the standard blackbody, there will be obtained a measure, in terms of a current through the pyrometer filament, of a brightness that is some known fraction of that of the standard blackbody at the standard temperature. If monochromatic radiation is used, it is easy to calculate the temperature, $T_2$, of the blackbody corresponding to this measured brightness; that is, to this current through the pyrometer filament from $T_1$, the standard temperature, by the following formula derived from Wien's equation:

$$\log R = \frac{c_2 \log e}{\lambda}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{10}$$

Where $R$ is the transmission of the sector or absorbing glass, $T_1$ the standard temperature on the absolute Centigrade scale, and $\lambda$ the wavelength used. If the measurements are made with a red glass in the eyepiece, the temperature, $T_2$,

TABLE 7

*Temperatures corresponding to different fractions of the radiation from a blackbody held at the temperature of melting palladium (1827°K) using a red glass with an effective wavelength which varies as is shown in column two*

($c_2$ = 14320$\mu$ deg.)

| TRANSMISSION OF SECTOR | $\lambda_e$ | $T_2$ |
|---|---|---|
| | $\mu$ | °K |
| 0.749 | 0.6654 | 1783 |
| 0.499 | 0.6655 | 1725 |
| 0.2443 | 0.6656 | 1632 |
| 0.0830 | 0.6658 | 1508 |
| 0.0336 | 0.6660 | 1418 |
| 0.01668 | 0.6662 | 1355 |
| 0.00543 | 0.6665 | 1265 |

corresponding to this fraction of the brightness of the standard blackbody, can be calculated just as before, except that in this case the effective wavelength of the red glass for this temperature interval is to be used. By using a number of such sectors, or absorbing screens, points can be obtained for a curve showing the relation between the temperature and the current through the pyrometer filament. In Table 7 is given the transmission value of a number of sectors and the apparent temperatures, $T$, that would be obtained by their use in connection with a blackbody held at the temperature of melting palladium.

## EXTENDING THE TEMPERATURE SCALE

The filament of the pyrometer lamp should not be heated to too high a temperature if it is to hold its calibration for any length of time. A safe temperature for a tungsten filament is somewhere in the neighborhood of 2000°K. Since it is often necessary to measure temperatures much higher than this, some means, such as a rotating sector or an absorbing glass to reduce the apparent brightness of the source, must be provided.

If a rotating sector or an absorbing glass of known transmission is used between the source being investigated and a calibrated pyrometer lamp, the calibration of this pyrometer with the sector or absorbing glass can be extended above the standard blackbody. In this case, the temperature of the source whose brightness is thus compared with that of the standard is to be calculated from the temperature corresponding to the current through the pyrometer filament and the transmission of the sector or absorbing glass used by means of formula 10, except that for this computation, $R$ is the reciprocal of the transmission of the sector or absorbing glass and then $T_2$ will come out greater than $T_1$. Successive approximations must be used as the extrapolated temperature must be known before the proper effective wavelength can be found. A very convenient method is to work out the extrapolated temperatures for the various sectors, as shown in Table 8.

TABLE 8

*Extrapolated temperatures, using red glass, for various sectors with transmission as given* $c_2 = 14320\mu$ deg.

| Transmission of sector... | 0.2443 | | 0.0830 | | 0.01664 | | 0.00542 | |
|---|---|---|---|---|---|---|---|---|
| Initial Temperature | $\lambda e$ | °K | $\lambda e$ | °K | $\lambda e$ | °K | $\lambda e$ | °K |
| °K | $\mu$ | | $\mu$ | | $\mu$ | | $\mu$ | |
| 1200 | 0.6675 | 1303 | 0.6673 | 1398 | 0.6670 | 1555 | 0.6668 | 1693 |
| 1300 | 0.6671 | 1421 | 0.6668 | 1530 | 0.6665 | 1727 | 0.6663 | 1899 |
| 1400 | 0.6667 | 1541 | 0.6664 | 1672 | 0.6661 | 1909 | 0.6659 | 2119 |
| 1500 | 0.6663 | 1663 | 0.6660 | 1816 | 0.6657 | 2100 | 0.6654 | 2354 |
| 1600 | 0.6659 | 1788 | 0.6656 | 1964 | 0.6652 | 2299 | 0.6650 | 2610 |
| 1700 | 0.6655 | 1913 | 0.6652 | 2117 | 0.6648 | 2511 | 0.6646 | 2887 |
| 1800 | 0.6651 | 2042 | 0.6648 | 2274 | 0.6645 | 2738 | 0.6643 | 3185 |
| 1900 | 0.6647 | 2171 | 0.6645 | 2434 | 0.6642 | 2967 | 0.6640 | 3514 |

In this table are given a series of extrapolated temperatures using different sectored disks. In column 1 are given the initial temperatures; that is, the ones corresponding to the pyrometer reading without any sector, and in the other columns are given the effective wavelength for the red glass used (curve C, Fig. 10) and the extrapolated temperatures corresponding to the same pyrometer readings when the sector whose transmission is given at the head of the column is used between the pyrometer lamp and the source studied. When these extrapolated temperatures are plotted against the initial temperatures, the extrapolated temperatures corresponding to any pyrometer reading can be obtained. A like set of curves can be made for a series of absorbing glasses of known transmission. Such curves can then be employed with any pyrometer having the same red glass, provided the same sectors or absorbing glasses are used.

### ROTATING SECTORS

A few words might well be said concerning the rotating sector disks that are used in calibrating the pyrometer or in extending the scale beyond that for which

the pyrometer is calibrated directly. A rotating sector that has been carefully calibrated, if used properly, is without doubt the best means that can be used for cutting down the apparent intensity of a source that is being studied. This is the method that has been used with the standard optical pyrometer for all the work at Nela Park. The sector disks, Fig. 13, used for this work, are about 36 cm in diameter and, except for those of small transmission—open part 4° or lower—have six equally spaced openings. The 4° sector has four equally spaced openings and the 2° sector has two openings equally spaced. These sectors are rotated by a motor, with speed controlled by a resistance in series, so that they can be run up to speeds of 4500 R.P.M., which has been found fast enough for a sector of one 1° opening. These sectors are generally referred to

FIG. 13. Rotating sector

by giving their opening in degrees. The number of sectors and the transmission given in Tables 7 and 8 have been found satisfactory for this type of calibration and use. The transmission of the sectors or absorbing glasses must be known to about one-tenth of one percent for accurate work. A one percent error in the transmission (0.0833) of a 30° sector, if the sector is used to extend the temperature scale above the palladium point (1827°K), will result in an error of about 3°. This error will, of course, be smaller for a like error in the transmission of a sector of larger transmission and vice versa. The sector must rotate at such a speed that no flicker is noticeable. To accomplish this, the alternations must be at least 30 to 40 per second. This is for the condition where the open and closed spaces of the sector are about equal in size. If there is a very great difference between the open and closed parts of the sector, as for instance in the

case of the 2° sector with two 1° openings, the speed must be higher. If the motor available will not rotate the sectors fast enough when there is but one opening and one closed part, it is often a great help to make more open spaces. For a sector of this diameter and a transmission as small as 1/360; that is, having a 1° opening, this will not work because if the sector opening is too small there is danger of an error due to diffraction. In this case, it is necessary to have a motor that will rotate at something like 3500 R.P.M. If the sector is not rotated fast enough the resulting flicker is bothersome when trying to make brightness comparisons, and errors are apt to be made.

### POSITION OF ROTATING SECTOR

If a rotating sector is used with a disappearing-filament optical pyrometer to reduce the apparent brightness of the background, care must be taken as to its location[12]. If the sector is placed near the lens, the image of a small source, or the edges of a large source, may not be clear. This is probably due to diffraction caused by using a part of the lens. This may cause a marked difference in the results of temperature measurements, depending on whether the sector is located near the objective lens or as near as possible to the pyrometer lamp. There is also a difference depending on the relative orientation of the openings in the sector and the source, provided the source is a lamp filament.

TABLE 9

*Errors in temperature measurements due to improper location of sector*

| POSITION OF 2° SECTOR | NEAR LENS | | NEAR PYROMETER LAMP | |
|---|---|---|---|---|
| | Opening of Sector Parallel to Background Filament | Opening of Sector Perpendicular to Background Filament | Opening of Sector Perpendicular to Background Filament | Opening of Sector Perpendicular to Background Filament |
| Current, in amperes through pyrometer filament for brightness match... | 0.3332 | 0.3354 | 0.3357 | 0.3357 |
| Apparent relative brightness..... | 0.9390 | 0.9950 | 1.0000 | 1.0000 |
| Temperature of background for these readings in °K..... | 2263 | 2275 | 2277 | 2277 |

In Table 9 are given results of a test showing the effect of the position of the sector. A 15 mil (0.381 mm) tungsten lamp operated at a brightness temperature of about 2275°K was used as a background and readings were made on the current through a 2.5 mil tungsten pyrometer filament, for an apparent brightness match with a sector having two 1° openings. From the table it can be seen that the position of a sector of this size can cause an error of about 14°K for this condition if care is not taken as to its location.

### ABSORBING SCREENS FOR OPTICAL PYROMETRY

For commercial work, absorbing glasses are generally used, due to the difficulty of mounting the sector so that it can be moved about with the pyrometer. When

properly calibrated and properly used, absorbing glasses are very satisfactory for this purpose. When it is necessary to use an absorbing screen, the main requirements are first to keep the absorbing glass clean, and to have some means so that the absorbing glass can always be put back in exactly the same place, because its transmission will vary with the angle the transmitted radiation makes with its surface. Another requirement is to have a screen that approximates a neutral tint sufficiently well to enable comparisons in brightness to be made by different observers that are in agreement to within the error allowed. The degree to which it is necessary for the absorbing screen to have a spectral transmission independent of the wavelength depends on the so-called monochromatic glass used in the eyepiece. It is evident that if this eyepiece glass is absolutely monochromatic, any absorbing glass will answer.

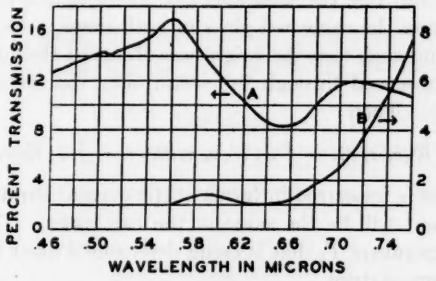


FIG. 14. Spectral transmission of various absorbing glasses. Curve A: Jena absorbing glass 1.5 mm. thick. Curve B: Noviweld obtained from Corning Glass Works. Shade about 6.

In Fig. 14 are shown the spectral transmissions of a piece of Noviweld (curve C) and a piece of Jena absorbing glass (curve B). Either of these glasses is nearly enough neutral tint for use with the red glasses having transmission curves shown by B, C, and D in Fig. 9.

The transmission of the absorbing glass when used with a red glass can be calculated for any blackbody distribution by the following formula from Preston's "Theory of Light":

$$\bar{\tau}_B = \frac{\int J_\lambda K_\lambda \tau_R \tau_B d\lambda}{\int J_\lambda K_\lambda \tau_R d\lambda} \tag{11}$$

where $J_\lambda d\lambda$ = blackbody energy for interval $\lambda$ to $\lambda + d\lambda$, $K_\lambda$ = luminosity, $\tau_R$ and $\tau_B$ = spectral transmissions of the red glass and absorbing glass respectively. It is very evident that if the spectral transmission of the absorbing glass is different for different wavelengths, the total transmission will be a function of the temperature of the source under investigation. In using this formula for calculating total transmissions, as well as in determining the effective wavelength, the integral was found by the step-by-step method. Results can be obtained that are as accurate as desired by making the steps small enough. If the

two-thirds rule is used very accurate results can be obtained with fewer steps. Transmission values can thus be obtained that are as accurate as the data warrant. If the computation be carried out to too many significant figures and if such values of transmission are used in determining the effective wavelengths, the latter will, of course, appear to be extremely accurate, more so than the experimental data warrant.

An absorbing glass that is not strictly neutral tint is frequently used to cut down the apparent brightness of a source when measuring its temperature with an optical pyrometer having a red glass in the eyepiece. It has been thought that a different value of the effective wavelength of the red glass must be used in connection with the so-called neutral-tint glass from that used in connection with a rotating sector of the same transmission. In what follows it is shown that such is not the case, but that the same effective wavelength is to be used for both.

Suppose that, using the same red glass in both cases, a sector with a transmission $\tau_S$ were found such that the brightness observed through the black glass would equal that observed through the sector (i.e., the sector and glass have same transmission). Then

$$\int J_\lambda K_\lambda \tau_B \tau_R d\lambda = \int J_\lambda K_\lambda \tau_R \tau_S d\lambda = \tau_S \int J_\lambda K_\lambda \tau_R d\lambda \tag{12}$$

Since the brightness is measured in terms of the current through the pyrometer filament, this current will be the same in the two cases. This means that in both cases the temperature $T_2$ that is being determined must be calculated from the same initial temperature.

The question to be considered is what effective wavelength is to be used in calculating the temperature of the source whose brightness is thus measured. When the brightness is measured, using the rotating sector, the temperature $T_2$ is calculated from the transmission of the sector and $T_1$, the temperature corresponding to the pyrometer reading when no sector is employed. For this calculation the following formula, derived from Wien's equation, is used:

$$\frac{1}{T_2} - \frac{1}{T_1} = \frac{\lambda_e \log \tau_s}{c_2 \log e} \tag{13}$$

In this expression $\lambda_e$ is the ordinary effective wavelength between $T_1$ and $T_2$, and is defined as the wavelength such that the ratio of the intensities of radiation for the temperature interval for this wavelength shall equal the ratio of the integral brightnesses through the screen used, or, stated in the form of an equation,

$$\left[\frac{J(\lambda T_1)}{J(\lambda T_2)}\right]_{\lambda_e} = \frac{\int J(\lambda T_1) K_\lambda \tau_R d\lambda}{\int J(\lambda T_2) K_\lambda \tau_R d\lambda} \tag{14}$$

When the brightness is measured with the use of an absorbing glass, the temperature $T_2$ must be calculated from the transmission of the absorbing glass and $T_1$, the temperature corresponding to the pyrometer current when no

absorbing glass is used. Inasmuch as we know the ratio of the brightness of the blackbody at the unknown temperature $T_2$ to that of the blackbody at temperature $T_1$, the temperature $T_2$ is to be calculated by an equation similar to equation 13; that is, by

$$\frac{1}{T_2} - \frac{1}{T_1} = \frac{\lambda_e' \log \tau_B}{c_2 \log e} \tag{15}$$

where $\lambda_e'$ is an effective wavelength. As $T_1$ and $T_2$ are the same in equations 13 and 15,

$$\lambda_e \log \tau_s = \lambda_e' \log \tau_B \tag{16}$$

whence

$$\lambda_e = \lambda_e' \tag{17}$$

That is, since the transmission of the absorbing glass given by equation 11 is the same as that obtained experimentally by comparing its transmission with that

TABLE 10

*Transmission of absorbing glasses at various temperatures*

| TEMPERATURE | NOVIWELD ABSORBING GLASS | JENA ABSORBING GLASS |
|---|---|---|
| °C | % | % |
| 20 | 1.70 | 8.96 |
| 102 | 1.55 | 8.90 |
| 200 | 1.39 | 8.87 |

of a sector, the same effective wavelength of the red glass is to be used with both the absorbing glass and a sector having the same transmission.

Thus to calculate the extrapolated temperature of a source whose brightness is measured through an absorbing glass, it is necessary to know the transmission of the glass as a function of the temperature of the source studied, because in calculating this extrapolated temperature the transmission of the screen to use is the one corresponding to the temperature that is measured. Also, just as with the sector, the ordinary effective wavelength, defined by equation 6, for the red glass used must be known before the final temperature can be accurately calculated. The calculation is therefore one of successive approximations, and in this case additional care is required, because both the effective wavelength and the transmission of the absorbing glass depend upon the temperature reached. When the effective wavelength of the red glass and the transmission of the absorbing glass are known, the extrapolated temperature is calculated by means of formula 10.

The total transmission of absorbing screens may also depend upon the temperature of the screens themselves. In Table 10 are given the total transmissions for two different temperatures of the screens, the spectral transmission of which are given in Fig. 14.

In connection with some special work† it was necessary to extend the calibration of an optical pyrometer to measure temperatures up to about 6000°K. This was done by using two absorbing glasses between the pyrometer lamp and the source being investigated. The spectral transmissions of the two glasses are shown by curves A and B, Fig. 15, and that of the combination is shown by curve

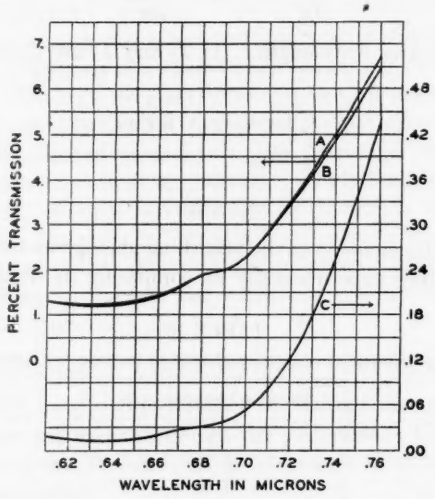


FIG. 15. Spectral transmission of two absorbing screens (Curves A and B) and the spectral transmission of the two together (Curve C).

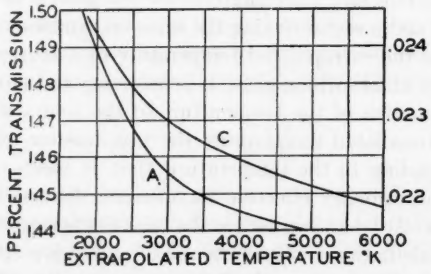


FIG. 16. Total transmission for red radiation of the absorbing screen whose spectral transmission is shown by Curve A, Fig. 15, and of the two absorbing glasses whose spectral transmission is shown by Curve C, Fig. 15.

C. The spectral transmission for any wavelength for the two glasses used together is the product of their separate transmissions for the same wavelength, corrected, of course, for the inter-reflections between them, which would be small.

† This calibration was made for the late Mr. G. M. J. MacKay of the Research Laboratory of the General Electric Co., at Schenectady.

The transmission of either of these glasses alone was readily measured while a single absorbing glass with a transmission equal to that of the combination of the two would have been very difficult to measure. The total transmissions of these absorbing glasses for red radiation were calculated from their spectral transmissions by formula 11 for various temperatures of incident radiation and are shown in Fig. 16. From the values of the total transmissions thus obtained, the extrapolated temperatures for one glass and for the combination of the two were calculated by means of equation 10 and are shown in Table 11. It will be seen that when the two glasses are used together, temperatures may be measured up to about 6000°K.

These values of extrapolated temperatures were calculated by means of Wien's equation, and are in error by the amounts shown in Table 1. This error is negligible except at the very high temperatures.

TABLE 11

*Extrapolated temperatures, using red glass, for one absorbing glass and for two absorbing glasses having the transmissions shown in Figs. 15 and 16*

$c_2 = 14320\mu$ deg.

| INITIAL TEMPERATURE | TRANSMISSION OF ONE ABSORBING GLASS | EXTRAPOLATION TEMPERATURE FOR ONE ABSORBING GLASS | TRANSMISSION OF TWO ABSORBING GLASSES | EXTRAPOLATED TEMPERATURE FOR TWO ABSORBING GLASSES |
|---|---|---|---|---|
| °K | | °K | | °K |
| 1200 | | | 0.000238 | 2228 |
| 1300 | | | 0.000233 | 2604 |
| 1400 | 0.0149 | 1922 | 0.000230 | 3045 |
| 1500 | 0.0148 | 2115 | 0.000227 | 3565 |
| 1600 | 0.0147 | 2321 | 0.000224 | 4143 |
| 1700 | 0.0147 | 2539 | 0.000221 | 4965 |
| 1800 | 0.0146 | 2770 | 0.000218 | 5942 |

## SECONDARY STANDARDS

Not every user of an optical pyrometer, indeed, not all research laboratories, have the facilities to make a check on the calibration on the pyrometer against a blackbody. This is because it is a difficult and time-consuming job to operate a blackbody every time it is necessary to check the calibration of the pyrometer. To avoid this waste of time it was decided to calibrate tungsten-filament lamps for the brightnesses, as measured with the optical pyrometer, of the blackbody at the two standard points. Two vacuum tungsten lamps, T-100 and T-116, (Fig. 17) with 7.5 mil single-loop filaments were used for such secondary standards. A particular part on the lower section of the loop of each filament was selected and the currents through the filament adjusted so that this part of the filament had the same brightness, as measured with the optical pyrometer, as the blackbody for each of the standard temperatures. The part of the filament selected was so uniform in temperature that no difficulty was experienced in measuring and checking the brightness.

The brightness of the blackbody at the two standard temperatures and the accuracy of the transfer of this brightness to the two standard lamps were checked a number of times during a period of about ten years, and thus the value of the currents through these two filaments for brightnesses the same as the blackbody at the palladium point and at the gold point were well determined. These two standard lamps have proven to be valuable as standards for checking the calibration of the optical pyrometers and are still in use for this purpose.

The blackbody furnace has not been operated at the laboratory at Nela Park for several years, so the temperature scale has been maintained by the use of these two calibrated standard lamps, T-100 and T-116.

In 1937 the brightnesses of these two lamps, as measured with the optical pyrometer having the red glass in the eyepiece, were checked at the National Bureau of Standards[15], and it was found that the mean brightness of the two

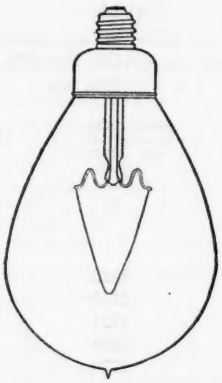

FIG. 17. The filament and bulb of T-100 and T-116. This bulb is about 5 inches in diameter

filaments for the current that had been used to bring them to the brightness corresponding to the melting point of palladium was that of a blackbody at 1829.6°K on the International Temperature Scale. On this scale the melting point of palladium has been found[16] to be 1827°K with $c_2$ taken as 14320 $\mu$°. Since we have been using the mean brightness of these two filaments to correspond to a temperature of 1829°K, using $c_2$ as 14320 $\mu$°, it is to be noted that the temperature in use at Nela Park is in good agreement with the International Temperature Scale.

A 7.5 mil wire is not a large enough source for calibrating commercial optical pyrometers. For this purpose a 3 mm ribbon filament makes a satisfactory source. A small notch is generally made on one side of the filament to indicate the position for observation.

When calibrating and using a tungsten filament lamp as a secondary standard for this purpose, care must be taken to see that the monochromatic screen having

the same effective wavelength is used on the pyrometer that is being checked that was used with the pyrometer making the calibration, or a correction must be made for the difference in their effective wavelengths. The error that is introduced due to this difference in the monochromatic screen depends upon the variation in effective wavelengths. From the conditions that hold for color match and Wien's equation, it can be shown that the error introduced by changing the effective wavelength for $\lambda_1$ to $\lambda_2$ is given by the following formula:

$$\left(\frac{1}{S_2} - \frac{1}{T_c}\right) = \frac{\lambda_2}{\lambda_1}\left[\frac{1}{S_1} - \frac{1}{T_c}\right] \tag{18}$$

where $T_c$ is the color temperature of the tungsten filament corresponding to a brightness temperature of $S_1$. Thus, if a secondary standard with a tungsten filament is calibrated using a red glass that has an effective wavelength of 0.665 $\mu$, and if this standard is used for checking the calibration of a pyrometer that has an effective wavelength of 0.656 $\mu$, an error of about 2° will result at a temperature of 1827°K and an error of about 4° at a temperature of 2500°K.

It is interesting to note that the tungsten pyrometer filament is hotter than the blackbody when they are at a brightness match as obtained with the pyrometer. The transmission of the lenses and the bulb wall of the pyrometer lamp, through which the radiation from the standard blackbody must pass before its image can be matched in brightness with that of the pyrometer filament, have a combined transmission of about 65 percent. This means that the image of the blackbody will only be 65 percent as bright at this point as the blackbody itself. The emissivity of the tungsten filament for red radiation ($\lambda$ = 0.665 $\mu$) for this temperature (1827°K) is about .44. Thus its brightness is only 44 percent that of the blackbody at this temperature. Therefore the brightness of the filament will have to be increased about 48 percent (above that for a tungsten filament at a temperature of 1827°K) before it will be bright enough to match the image of the blackbody. This means an increase in temperature of about 63° for wavelength of 0.6650 $\mu$. For wavelength of 0.656 $\mu$, this difference would only be 62°. It is sometimes thought that the current through a tungsten pyrometer filament would not differ an appreciable amount for brightness matches with a blackbody when using red glasses that differed as slightly as this in their effective wavelengths. This 1° difference found for the effective wavelength change from 0.665 $\mu$ to 0.656 $\mu$ could easily be detected by careful measurement at this point.

## ACCURACY TESTS

A number of tests have been run to find the accuracy that might be expected from different types of observers in the use of the disappearing-filament type of optical pyrometer. The first test was made by a number of inexperienced observers using a laboratory form of pyrometer. The results are shown in Table 12. Observers 1 and 2 were high-school graduates with several months' experience as laboratory assistants. Observer 3 was a man with several years' shop experience. Observer 4 was a man with several years' experience in a lamp

factory. Observer 5 had no experience with this kind of work, and Observer 6 had no experience with the photometer. The table shows that but a single observer made an error of 3°K from the average.

Four experienced observers made readings with different types of red glass, using either a sector or piece of absorbing glass to cut down the apparent intensity of the source. Table 13 shows the results that were obtained.

TABLE 12

*Results obtained with a disappearing-filament type of pyrometer by inexperienced observers*

| OBSERVER | VALUE OBTAINED FOR TEMPERATURE, AS AN AVERAGE OF SIX READINGS | | VARIATION OF SINGLE READINGS FROM MEAN |
|---|---|---|---|
| | °K | °K | °K |
| Standards | 1438 | 1643 | |
| (1) L. C. | 1439 | 1643 | 4 |
| (2) H. W. | 1438 | 1642 | 3 |
| (3) F. G. | 1439 | 1642 | 2 |
| (4) E. H. | 1436 | 1644 | 3 |
| (5) E. W. | 1436 | 1636 | 5 |
| (6) L. R. | 1436 | 1640 | 2 |

TABLE 13

*Results obtained by experienced observers using different red glasses and different absorbing glasses*

| OBSERVER | CURRENT IN AMPERES THROUGH PYROMETER FILAMENT FOR APPARENT BRIGHTNESS MATCH WITH | | | | |
|---|---|---|---|---|---|
| | Red glass used | Direct | 2° Sector | Noviweld absorbing glass | Two Jena absorbing glasses |
| I. A. V. | Jena No. 4512 | 0.4343 | 0.3358 | 0.3804 | 0.3547 |
| K. H. M. | Jena No. 4512 | 0.4343 | 0.3361 | 0.3807 | 0.3546 |
| W. E. F. | Jena No. 4512 | 0.4343 | 0.3361 | 0.3803 | 0.3546 |
| A. G. W. | Jena No. 4512 | 0.4343 | 0.3358 | 0.3805 | 0.3547 |
| I. A. V. | Corning Red | | 0.3380 | 0.3784 | |
| K. H. M. | Corning Red | | 0.3380 | 0.3785 | |
| W. E. F. | Corning Red | | 0.3380 | 0.3783 | |
| A. G. W. | Corning Red | | 0.3378 | 0.3784 | |

A third experiment shows in another way what results are expected with the optical pyrometer. A number of lamps[17] were calibrated at the Nela Park laboratory and sent to the National Bureau of Standards, the National Physical Laboratory of England, the Physikalisch-Technischen Reichsanstalt in Berlin, the Laboratoire Central in Paris, the General Electric Research Laboratory at Schenectady, the Physics Laboratory at the University of Wisconsin, the Laboratory of the Philips Glowlampworks in Eindhoven, and the laboratory of the Osram Lamp Company at Berlin. Taking in all errors of the results of the measurements, changes in the lamps or any change whatsoever, the maximum

error found in any one lamp was about 15°; the average error considerably less. In this case, the pyrometers were calibrated and measurements made in different laboratories.

In connection with the establishment of the Waidner and Burgess[18] standard of light intensity, which is the brightness of a blackbody at the freezing point of platinum, the melting point of platinum was measured at three standardization laboratories with the results shown in Table 14. These temperatures were measured with the disappearing-filament optical pyrometer; thus they indicate the high accuracy that can be obtained when special care is taken with all sources of error.

A test was made by Dr. N. K. Chaney[19] of the National Carbon Company which shows further the accuracy that can be obtained in using the optical pyrometer. Dr. Chaney found that a properly operated carbon arc reached a

TABLE 14

*Melting point of platinum as determined in connection with establishment of Waidner and Burgess standard of light intensity*

| | |
|---|---|
| National Bureau of Standards | 1773.5°C |
| National Physical Laboratory | 1773.3 |
| Physikalisch-Technischen Reichsanstalt | 1773.8 |

TABLE 15

*Brightness temperature of a special carbon arc as measured in three laboratories*

| | |
|---|---|
| National Carbon Company | 3814°K |
| Nela Park | 3812* |
| National Bureau of Standards | 3821 |

* Corrected to international temperature scale since data published by Dr. Chaney.

very steady temperature. This was measured in three laboratories with results shown in Table 15.

## NON-BLACKBODIES

As has been pointed out, the optical pyrometer as calibrated and used gives the brightnesses of the observed surface for a definite wavelength interval, which wavelength interval is given by the range of wavelengths transmitted by the particular so-called monochromatic screen used in the eyepiece to limit the wavelength interval employed. The value for the true temperature must be obtained from these brightness measurements and the only body for which the relation between the surface brightness and temperature is known from theory is the blackbody, and for this it is given by Wien's equation within the limitations already discussed (Table 1).

The radiating characteristics of many metals and some non-metals as well can be studied by mounting small filaments of these materials so they can be heated by the passage of an electric current. To keep the material from oxidizing and

also to protect them from air currents, such filaments are often mounted in lamp bulbs which are either evacuated or filled with an inert gas.

TABLE 16

*Changes in temperature of 2400° and 3000°K extrapolated from 1800°K as initial temperature, using Wien's equation, due to various changes*

| VARIATION LEADING TO ERROR | PERCENTAGE CHANGE | | | ACTUAL CHANGE (°K) | | |
|---|---|---|---|---|---|---|
| | 1800°K | 2400°K | 3000°K | 1800°K | 2400°K | 3000°K |
| Change of 1% in initial temperature | 1.0 | 1.30 | 1.70 | 18.0 | 32.0 | 50.0 |
| Change of 3°K in initial temperature | | | | 3.0 | 0.5 | 8.0 |
| Using a wavelength, 1% in error | | 0.30 | 0.70 | | 8.0 | 20.0 |
| 0.001$\mu$ error in wavelength | | 0.50 | 0.10 | | 1.2 | 3.0 |
| If in extrapolating the $\lambda_\epsilon$ of red glass between 1300° and 1800°K is used (see Fig. 11) | | 0.10 | 0.30 | | 2.4 | 7.5 |
| Calibrating pyrometer filament against tungsten lamp as background that was standardized with a red glass different from one used in pyrometer being calibrated. Suppose $\lambda_\epsilon$ to change from 0.665$\mu$ to 0.650$\mu$ | | | | 3.5 | | |
| Error of 1% in value used for transmission of sector or absorbing glass | | 0.11 | 0.14 | | 2.7 | 4.2 |
| Variation of 1% in current through 2½-mil pyrometer filament | 0.5 | 0.70 | 0.80 | 9.0 | 16.0 | 25.0 |

TABLE 17

*Corrections in °C to add to brightness temperature readings for different emissivity*

| EMISSIVITY | PYROMETER USING RED LIGHT, WAVELENGTH, $\lambda$ = 0.665 AND $c_2$ = 14320$\mu$° AT OBSERVED TEMPERATURES, DEGREE KELVIN, OF | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1000 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 | 1800 | 2000 | 2200 | 2400 | 2600 | 2800 | 3000 | 3600 |
| 0.10 | 120 | 147 | 177 | 210 | 246 | 287 | 330 | 378 | 429 | 544 | 677 | 828 | 1001 | 1197 | 1417 | 2252 |
| 0.20 | 81 | 98 | 118 | 140 | 164 | 189 | 217 | 248 | 280 | 352 | 433 | 524 | 627 | 741 | 867 | 1325 |
| 0.30 | 59 | 72 | 86 | 102 | 119 | 137 | 157 | 179 | 201 | 252 | 308 | 372 | 442 | 520 | 605 | 907 |
| 0.40 | 44 | 54 | 64 | 76 | 89 | 102 | 117 | 132 | 149 | 186 | 227 | 273 | 323 | 379 | 439 | 651 |
| 0.50 | 33 | 40 | 48 | 57 | 66 | 76 | 87 | 98 | 110 | 137 | 167 | 201 | 237 | 277 | 320 | 472 |
| 0.60 | 24 | 29 | 35 | 41 | 48 | 55 | 63 | 71 | 80 | 99 | 121 | 145 | 170 | 199 | 230 | 336 |
| 0.70 | 17 | 20 | 24 | 29 | 33 | 38 | 43 | 49 | 55 | 68 | 83 | 99 | 117 | 136 | 157 | 228 |
| 0.80 | 10 | 13 | 15 | 18 | 21 | 24 | 27 | 30 | 34 | 42 | 51 | 61 | 72 | 84 | 96 | 140 |
| 0.85 | 7.6 | 9.2 | 11.0 | 12.9 | 15.0 | 17.2 | 19.6 | 22.1 | 24.8 | 30.6 | 37.1 | 44.3 | 52.1 | 60.4 | 69.5 | 100.5 |
| 0.90 | 4.9 | 5.9 | 7.1 | 8.3 | 9.6 | 11.0 | 12.6 | 14.3 | 16.0 | 19.7 | 23.9 | 28.5 | 33.5 | 38.9 | 44.7 | 65.0 |
| 0.95 | 2.4 | 2.9 | 3.5 | 4.1 | 4.7 | 5.4 | 6.1 | 6.9 | 7.7 | 9.6 | 11.6 | 13.8 | 16.1 | 18.8 | 21.5 | 31.3 |

The values given in this table also give the correction for a window having a transmission given in column 1 for different temperatures of the source when this window is used between the source and the pyrometer.

If measurements of temperature are made through any type of window or a lamp bulb, some correction is necessary. This correction depends upon the transmission of the window or bulb. The data in Table 17 shows these corrections for various values of transmission when the column marked "Emissivity" is to be used as the transmission.

### BRIGHTNESS TEMPERATURE OF NON-BLACKBODIES

The radiation characteristics of many materials in the visible spectrum can be very readily studied in terms of their surface brightness by the use of the optical pyrometer, and if proper precautions are taken, quite accurate results can be obtained. Most non-blackbodies can be so prepared; i.e., surface conditions, that their radiating conditions are quite constant for any definite temperature. From the definition of a blackbody and Kirchhoff's Law, all non-blackbodies that owe their brightnesses to thermal causes alone are less bright when at a particular temperature than the blackbody at the same temperature. Thus if temperatures of any of these non-blackbodies are calculated from measurements of their brightness, as though they were blackbodies—this means using the relation between surface brightness and true temperature for a blackbody—values that are lower than the true temperature will be obtained. The temperature obtained, however, is the temperature that a blackbody must have in order to give the same brightness for the particular wavelength interval as the body being investigated. Since such temperatures are obtained from the measurement of the brightness of non-blackbodies treated as blackbodies, these temperatures are called blackbody brightness temperatures, or shortened to brightness temperatures, and are designated $S_\lambda$, the subscript indicating the wavelength used. Thus if a non-blackbody has the same brightness, as measured with the optical pyrometer, as a blackbody at 1500°K, it will be said to have a brightness temperature of 1500°K, which is lower than the true temperature. The value of the brightness temperature generally varies with the wavelength interval used. Thus the brightness temperature of tungsten for a true temperature of 2170°K is 2000°K for red radiation ($\lambda = 0.665\ \mu$) and 2058°K for blue radiation ($\lambda = .467\ \mu$. The difference between the true temperature and the temperatures thus obtained varies from a few degrees for such substances as untreated carbon to more than 200°K for such material as polished platinum at its melting point.

### TRUE TEMPERATURES OF NON-BLACKBODIES

To obtain the true temperature of non-blackbodies from the measured brightness temperature requires a knowledge of radiating characteristics of the surface studied. In this particular instance, it is necessary to know the ratio of the brightness of the source studied to that of the blackbody at the same temperature and for the same wavelength interval. This ratio is called the emissivity, and values of this emissivity have been determined for a number of metals and other substances for different temperature intervals. A list of the emissivity of various materials is given in Table 18.

Worthing[20] has shown how the emissivity for metals can be obtained with the optical pyrometer. To do this a blackbody was made of the material studied. Such blackbodies were in the form of a long tube with small radial holes for observation purposes and these tubes mounted in a lamp bulb so they could be heated electrically. Since such tubes contain a cavity with uniformly heated

walls, this cavity contains blackbody radiation which is observed through the small radial holes. Measurements with the optical pyrometer of the radiation from the small radial holes thus gives the true temperature and the brightness of the blackbody for this temperature and observation of the surface near the holes gives the brightness of the material studied for the same temperature. For the highest accuracy, a slight correction must be made for the small difference in the temperature between the inside and outside walls of the tube.

TABLE 18

*Spectral emissivities for red radiation, λ as given, for a number of metals at several temperatures, taken from Worthing's data*

| TEMPERATURE | TUNGSTEN | TANTALUM | MOLYBDENUM | RHODIUM[2] | PLATINUM | PALLADIUM | NICKEL | IRON | SILVER | COPPER | GOLD |
|---|---|---|---|---|---|---|---|---|---|---|---|
| °K | μ | μ | μ | μ | μ | μ | μ | μ | μ | μ | μ |
| | 0.665 | 0.665 | 0.665 | 0.667 | 0.665 | 0.66 | 0.66 | 0.66 | 0.650 | 0.66 | 0.665 |
| 300 | 0.470 | 0.493 | 0.420 | | | | | | | | |
| 1000 | 0.456 | 0.459 | 0.390 | | | | | 0.27 | | | |
| 1200 | 0.452 | 0.450 | 0.382 | 0.242 | 0.29 | 0.36 | 0.25 | | 0.044 | 0.10 | 0.12[3] |
| 1500 | 0.445 | 0.438 | 0.371 | 0.242 | 0.30 | 0.33 | 0.23 | | | 0.13 | |
| 1800 | 0.439 | 0.426 | 0.360 | 0.242 | 0.31 | 0.30 | 0.21 | | | | |
| 2000 | 0.435 | 0.418 | 0.353 | 0.242 | | | | | | | |
| 2500 | 0.425 | 0.400 | 0.338 | | | | | | | | |
| 3000 | 0.415 | 0.384 | 0.328[1] | | | | | | | | |

[1] Melting point—2895°K.
[2] Highly outgassed.
[3] Solid—1336°K.

The true temperature, $T$, can be calculated from the brightness temperature, $S_\lambda$, and the emissivity, $\epsilon_\lambda$, by the following equation:

$$\left[\frac{1}{T} - \frac{1}{S_\lambda}\right] = \frac{\lambda \log e}{c_2 \log \epsilon_\lambda} \tag{19}$$

In Table 17 are given the values necessary to add to different values of brightness temperatures for different emissivities to obtain the true temperatures.

In some extended work Wahlin[21] has shown that the emissivity of many metals approaches a constant value, independent of the temperature, as the material is more completely outgassed.

Objections have often been made to the use of red glass screens in the eyepiece of the pyrometer—where measuring non-blackbodies—on the ground that as the range of wavelengths transmitted is so large, there is no method of knowing to what wavelength the resulting temperature was to be assigned.

When the brightness temperature of a source is determined with an optical pyrometer with a so-called monochromatic screen before the eyepiece, what is really measured is the brightness of the source through the screen. If a screen that is absolutely monochromatic is used before the eyepiece or if a spectropyrometer is used for these measurements, the wavelength will be quite definitely

determined and there will be no question concerning the wavelength used, and also it is at once evident to what wavelength the temperature of a non-blackbody thus measured should be ascribed. However, if a red glass is used, such as those having the transmission shown in Fig. 10, some consideration is necessary.

If the effective wavelength of the red glass filter used is known for different temperature ranges, the results can be treated just as definitely as if an absolutely monochromatic screen were used and, in addition, the red glass has the added advantage of transmitting enough light to enable very accurate brightness comparisons to be made.

### WAVELENGTH EFFECTIVE FOR BRIGHTNESS TEMPERATURE

One question is the wavelength to which this brightness temperature, $S$, should be ascribed. It will now be shown that the wavelength to which this brightness temperature, $S$, is to be ascribed is the effective wavelength for the temperature interval of a blackbody between a temperature $T$ $(= S_\lambda)$ and $T_c$, the color temperature of the source studied. The effective wavelength $\lambda_e$ for this temperature interval is

$$\frac{B_T}{B_{T_c}} = \left[\frac{J(\lambda T)}{J(\lambda T_c)}\right]_{\lambda_e} \tag{20}$$

where $B_T$ and $B_{T_c}$ represent the brightness of the blackbody at temperatures $T$ and $T_c$ through the screen used, and $J(\lambda T)$ and $J(\lambda T_c)$ represent the energy emitted (Wien's Equation) by a blackbody at temperatures $T$ and $T_c$.

Since the color temperature will be needed in the following it will now be defined[22]. The color temperature of a source at a particular temperature is the temperature at which it is necessary to operate a blackbody so that it will give light of the same integral color as the source studied. It has been found experimentally that most metals when heated radiate in such a manner that they can be color-matched against a blackbody and that these color matches are very easily and accurately made with an ordinary contrast photometer. When practically any source of continuous radiation (temperature radiation) is color-matched with a blackbody, it has very nearly the same spectral distribution as the blackbody at this temperature. When two bodies have the same color temperature, it is not necessary that they have the same brightness.

The brightness temperature, $S_\lambda$, must be ascribed to a wavelength such that the energy emitted by a blackbody per unit area at temperature $T(= S_\lambda)$, for this wavelength will equal that emitted per unit area by the source for the same wavelength. It is necessary to consider three sources: first, the non-blackbody studied which is at a brightness temperature, $S_\lambda$, and has a brightness $B_S$; second, the blackbody at a temperature, $T(= S_\lambda)$, which has a brightness $B_T = B_S$. This source has a distribution $J(T\lambda)$. The third source is the blackbody at temperature $T_c$ which is the color temperature of the source at brightness temperature $S_\lambda$. Its distribution is given as $J(\lambda T_c)$ and it has a brightness of $B_{T_c} = KB_T$. If each ordinate of its distribution is reduced by a factor $K$, the resulting distribution will be that of the source at brightness temperature $S_\lambda$.

Thus, there are two sources with different spectral distributions that have the same brightness when observed through the red screen, a blackbody at temperature $T(= S_\lambda)$ and the source studied, which is at a brightness temperature $S$ and has a color temperature of $T_c$. As these two distributions are different and yet the sources have the same brightness, curves representing these distributions must cross if they are plotted with energy emitted per unit area against wavelength. The point at which these two curves cross evidently gives the wavelength to which the brightness temperature, $S_\lambda$, is to be ascribed.

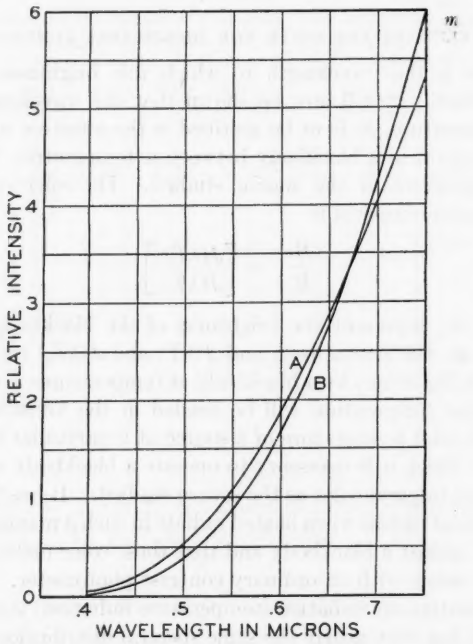


FIG. 18. Spectral energy of the source studied (Curve A) and spectral energy of the blackbody set for the same brightness (Curve B).

If the source studied is considered, it will be seen from the definition of color temperature that its distribution of energy corresponds to that of a blackbody at $T_c$, the difference being that each ordinate of the curve representing the blackbody distribution at temperature $T_c$ bears a constant ratio $K$ to the corresponding ordinate for the source studied. Thus the actual energy distribution of the source being investigated is given by $J(\lambda T_c)/K$. As stated, this curve and the one representing the distribution of a blackbody at the temperature $T$ will cross at the wavelength where $\frac{J(\lambda T_c)}{K} = J(\lambda T)$ (Fig. 18). The distribution of energy given by the source considered is shown in Fig. 18, curve A, and the distribution of energy from the blackbody at temperature $T(= S_\lambda)$ is given by curve B, Fig.

18. It is to be noted that if the ratio of the brightness of a blackbody at $T$ ($= S_\lambda$) to that of a blackbody at $T_c$ were measured with the optical pyrometer, using the filter under investigation in the eyepiece, the value found would be $K$. As each ordinate of the curve representing the distribution of energy from the source studied is a certain fraction $1/K$ of that for a blackbody at temperature $T_c$, the brightness will be reduced the same amount. Thus, if $B_s$ is the brightness of the source studied,

$$(B_s) = \frac{(B_{T_c})}{K}$$

$$B_{T_c} = K(B_s) \quad \text{and} \quad \frac{B_T}{B_{T_c}} = \frac{B_T}{KB_s} = \left[\frac{J(\lambda T)}{J(\lambda T_c)}\right]_{\lambda_e} = \frac{1}{K} \tag{21}$$

or

$$\frac{B_T}{B_s} = 1 = \left[\frac{\dfrac{J(\lambda T)}{J(\lambda T_c)}}{K}\right]_{\lambda_e} \tag{22}$$

Thus $J(\lambda T)$ and $\dfrac{J(\lambda T_c)}{K}$ are equal for the wavelength $\lambda_e$; in other words, the curves representing these two distributions cross at this point. From this it follows that the brightness temperature $S_\lambda$ is to be ascribed to the effective wavelength for the screen used for the temperature interval of a blackbody from $T(= S_\lambda)$ to $T_c$.

The wavelengths to which the emissivities of metals determined with an optical pyrometer are to be ascribed must be considered. It has been shown by a line of reasoning similar to that for the brightness temperature that such emissivities are to be ascribed to the effective wavelength of the screen used for the temperature interval between the color temperature and the true temperature of the source studied. This means that the brightness temperature and the emissivity are to be ascribed to slightly different wavelengths. For most metals studied the change to be made in either the brightness temperature or the emissivity for the small wavelength difference is very minute.

The above considerations show that when brightness temperature or emissivities are measured for different temperatures, using a monochromatic screen in the eyepiece, the results obtained are for different wavelengths. The values of the brightness temperatures can be reduced to a common wavelength, providing the corresponding color temperature is known, by the use of the following formula:

$$\frac{1}{S_{\lambda_2}} = \frac{\lambda_2}{\lambda_1}\left[\frac{1}{S_{\lambda_1}} - \frac{1}{T_c}\right] + \frac{1}{T_c} \tag{23}$$

Likewise the values of the emissivities can be reduced to the same common wavelength by the use of the following formula:

$$\log \frac{\epsilon_{\lambda_1}}{\epsilon_{\lambda_1}} = c_2 \log e \left(\frac{1}{T} - \frac{1}{T_c}\right)\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) \tag{24}$$

where $\lambda_1$ is the wavelength for which the emissivity is desired and $\lambda_2$ is the wavelength for which it was measured. The corrections to the values of the emissivities for the changes in the wavelength of the red glass, whose spectral transmission is shown by curve A, Fig. 18, are very small.

For much of the data used in this paper we are indebted to a number of our colleagues in this Laboratory, in particular, Miss Joyce Patnoe. We wish to express our appreciation for this help.

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# DENISON SCIENTIFIC ASSOCIATION

*Organized April 16, 1887*

## REPORT OF THE PERMANENT SECRETARY FOR THE YEAR 1943–1944

The following officers served the Denison Scientific Association during 1943–1944—another War year:

R. H. MAHARD, *President*
C. S. ADES, *Vice-President*
J. H. RUSH, *Recording Secretary and Treasurer*
W. C. EBAUGH, *Permanent Secretary and Editor*
L. E. SMITH, *Librarian*

The Life Science Building housed all meetings and the President was in charge of all gatherings of the Association, unless otherwise specified. The meetings were as follows:

*September 28, 1943*

Programs for the year, membership, and other matters of business were considered. Due significance was given to the effects of World War II upon the life of the Denison Scientific Association and to the results that it would have upon the organization and the lives and fortunes of its members and speakers.

*October 12, 1943*

MOLECULAR FILMS. W. A. EVERHART (Retiring President)

Investigations of the dimension and properties of molecular films were given by Langmuir and others, and are proving to be increasingly useful to the chemist, physiologist, biologist and physicist. To them they have given concrete evidences of the shapes and sizes of the molecules of which certain organic oils are composed, of the proteins themselves (perhaps the most complicated or organic structures), and of the behavior of materials where one end contains groups like those in hydrocarbons while the other end of relatively long molecules has carboxyl (—COOH) and similar groups. The lecture was well illustrated by actual experiments with oils of various kinds, Tinker-toy and more modern models, and by a movie film with Dr. Irving Langmuir, of the General Electric Laboratories, as principal demonstrator. The implications and results of the investigations were made available for work with these substances in the future.

*November 9, 1944*

ESTABLISHMENT OF BRITISH AIR LINE, ENGLAND TO INDIA, FOLLOWING WORLD WAR I. M. B. STRATTON

The British hoped to use the airship for main lines, with airplanes for feeders. The civil aviation, Cairo to Karachi, saved almost three weeks in going to

Baghdad, was a hold on the oil resources, and an aid to the Royal Air Force. In 1921 a military service route was established between Cairo and Baghdad, which also carried the mails and paved the way for a civilian service. In 1927, after much delay, Imperial Airways, Ltd. opened a commercial service between Cairo and Basra, which was expanded in 1929 to unite England with India. This air line has since been extended to South Africa and to New Zealand and is an important factor in Britain's defense of her empire in the present conflict. It was the government's intention to establish a lighter-than-airship service to India as well. Financial difficulties handicapped this program, but in 1924 two ships (for trial purposes) were ordered built. The crash of one of these ships on a trial trip to India, and the advent of the financial depression in that year, led to the suspension of activities. Advances in heavier-than-aircraft make it unlikely that the airship will be seriously considered for communication purposes after World War II. The air boat, getting away from airdromes, with their attendant economies, was great in comparison with other forms of aircraft.

*November 23, 1943*

## EVIDENCE OF THINGS NOT SEEN. J. H. Rush

Men in all the ages have believed in seers and prophets, hunches, ghosts, visions, intuition, and life after death. Serious ventures into "psychic research" by many eminent men have resulted in a few reliable findings, much disgust, and many dupes. In recent years controlled experiments have been made to determine whether the mind can acquire factual information independently of the known physiological senses. The basic phase of all religions is on the mystical side; that there is a flexible boundary between the proved and the unproved, striking similarities between the recorded observations of psychics, and the premonitions, hallucinations and apparitions of psychics and non-psychics alike, goes to show the great interest in this subject. As believers in a life after death and other phases of the positive value of such investigations may be mentioned Crookes, Lodge, Lombroso and others, as men who wanted to discredit the whole subject were Houdini and his co-workers of the "witch hunting" school. The work of MacDougal at Harvard, Rhine at Duke, Titchener at Cornell, Coover at Stanford, were cited in evidence of men who were making the positive approach. Fundamentally telepathy and clairvoyance were shown to be essentially alike in kind and method. Mathematically proof is offered in the realm of the theory of probability as to the validity of a conclusion. In the case of card games the overall average was above that shown in hit-or-miss guessing at results. This also shows that ability is affected by fatigue, sleep, distance, personal factors, time, emotional unbalance, etc. The later developments of prerecognition (prophecy), influencing of coming events by extra-physical (mental) processes, is shown by the throws of dice and drawing of cards. They are both related to extra-sensory perception. Implication of such findings for concepts of time, space, and relation of mind to matter are revolutionary. Such implications are distasteful to many (elder) scientists who rest on established faiths; they are inspiring to many (younger) scientists who seek new opportunity.

*December 14, 1943*

LESSONS FROM KNOTTED STRINGS. BONNIE M. STEWART

"Patience" is a virtue said to be inculcated in Boy Scouts by working with strings and knots. That it also applies to other ages and other times is shown by the forms recognized by anthropology, music and mathematics. Thus figures of the cat's cradle of the Asiatic type require two players, while the Oceanic type requires but one: they date from the 10th century and represent the world around. These figures made with a loop of string are found everywhere. Off the coast of Scotland is an Irish cemetery. The design of two panthers shows the notation of music, the Gregorian chant, or the portrayal of the resurrection. In this the knots of the string correspond to the design given, and is subject to various interpretations. The music hypothesis is untenable, according to some authorities. Knots in mathematics represent closed spaces or intersections on lines or pieces of strings, and bring up the whole theory of deformations, matrices, indices, vertices, determinants, closing points, vortex atoms, and other physical and mathematical constants. How many elements are possible? Let the information (via Kelvin, Tait, Kirkman et al.) come to one by way of knotted strings. The whole lecture was illustrated.

*January 11, 1944*

WHEN WE WERE VERY YOUNG. A. W. LINDSEY

A discussion of some of the strange beginnings of the human structures, when the nervous system lies on the outside of the body and opens into the intestines; when the heart and blood vessels are like those of a fish; and the kidneys show a strong resemblance to the excretory organs of the earthworm. The wonder of biological evolution from a single cell to an organism containing many million cells, the time of starting as an individual not determinable ("When is it the proper birthday of man?"), and many other questions were brought to light. The development of a human embryo from what it was at first to the normal and abnormal form, prolonged infancy of man, comparative brain size in animals at various ages, the nervous, circulatory and respiratory systems, a comparison of the gills of fishes and the lungs of man—all were presented by the lecture to show what man was "when very young"—i.e., when in the state of an embryo rather than a grown individual.

*January 25, 1944*

THE BIG INCH PIPE LINE. A. C. LADNER

Motion pictures, accompanied by a running description, showed what was done in the construction of the "Big Inch Pipe Line." This runs from Texas to Ohio, through all sorts of terrain and climates, and will help the gasoline situation in the East and overseas. It ought to be of great assistance in World War II in releasing many tank cars and ocean-going vessels from their task of carrying petroleum and its derivatives. The pipe line can do the work as well, if not better. It is a triumph of engineering skill.

*March 28, 1944*

HOW INVENTIONS GROW. W. C. EBAUGH

When one is accustomed to a thing how often is a thought given to the way it came to be? Yet the story may be one of absorbing interest, with implications and suggestions for future work never dreamed of when the investigation started. Recently the question was asked: "What professional accomplishment gave the most satisfaction to you?" An attempt was made to answer this query in part by reference to the early history of the conflict between the smelting and the agricultural industries of the semi-arid West, the origin of the Cottrell process in California, and the "Neufil," or neutralization-filtration method, in the Salt Lake Valley. Wonderful results have been obtained by applying them on a large scale. Instead of having smelters put out of commission by court injunctions they have been permitted to operate under specified conditions. After the lapse of many years the surrounding country is as productive as ever and commercial damage is negligible. Experiments from the beginning until Thomas's apparatus, which gives practically the momentary sulphur dioxide content of the air at upper as well as at lower reaches of the atmosphere, were shown. The effects of the sulphur dioxide and solids content of the atmosphere both are taken into consideration.

*April 11, 1944*

A dinner and business meeting at the Granville Inn was held, with President R. H. Mahard in the chair.

The Secretary's and Treasurer's reports were offered by the officer concerned, J. H. Rush; the Committee on Nomination offered the following names, which were duly chosen by the Secretary-Treasurer, *viz.:*

Chosaburo Kato, *President*
R. M. Meyers, *Vice-President*
J. H. Gibbud, *Secretary-Treasurer*
W. C. Ebaugh, *Permanent Secretary and Editor*
L. E. Smith, *Librarian*

A general discussion followed in which were taken up the (a) entertainment of the candidate for the Doctor of Science degree (b) JOURNAL OF THE SCIENTIFIC LABORATORIES OF DENISON UNIVERSITY (c) the Committee to suggest a name for the honorary degree that will continue the succession as in the past (d) programs and meetings for 1944–1945.

Only one number of our JOURNAL OF THE SCIENTIFIC LABORATORIES OF DENISON UNIVERSITY was issued:—the World War II has produced casualties in the journalistic field as well as among our young people. The contents are as follows, *viz.:*

Vol. 38, Articles 3–4, pp. 41–76, December, 1943

The Cranial Nerves. A review of Fifty Years. C. Judson Herrick. 12 pp.

Radiometric and Colorimetric Characteristics of the Blackbody between 2800°K and 3800°K. E. Q. Adams and W. E. Forsythe. 17 pp., 1 fig.

Report of the Permanent Secretary of the DENISON SCIENTIFIC ASSOCIATION. 8 pp.

"World War II" "Peace and Reconstruction" " Post-War Planning" "World War III to Come." Such were the slogans upon the campuses of our colleges and universities until June, 1945. With some ten million men and women in the Armed Forces of their country in the United States of America alone, with the selective draft making it impossible to tell from week to week how many or what students would be present a week or a month hence, and with women taking a predominant share in the activities of the laboratories and the colleges of our country, it was natural that the pattern of the life should change to meet the new conditions. Even a "small" college like Denison University, that normally held about 1000 students divided between the sexes with 600 men and 400 women, had a unit of the Air Corps of the Army, numbering about 250; of the Marines, some 225; of Navy V-12 men, about 300; of civilian men, about 75 or 100; and of civilian women, about 600. It is no wonder that Saturdays and nights were utilized, men's fraternity houses given over to women, women's dormitories to men in uniform, and civilian men compelled to seek rooms among the townspeople. The curriculum was changed. The conditions of graduation were altered. The returning veteran had a share in it all. Last, but by no means least, the casualty lists showed that the small colleges, as well as the large State universities, were having their share of dead, wounded, missing, and hospitalized. From faculty and student body alike these changes have come.

Orders, especially from the Scandinavian and Pacific countries, that can not be filled now are having their numbers of the JOURNAL printed as usual; they will be sent out as soon as the present conflict is ended. In conclusion a quotation from the JOURNAL of December, 1943, is as apt as ever:

"In the era of peace following World War II at some indefinite date, we can look forward confidently to continued scientific investigation, publication and progress. Much that cannot be printed now will be available then; the recognition of the part science has played in the all-out war effort on the production front as well as the fighting front will establish science more firmly than ever as a dominant factor in human affairs."

Respectfully submitted,

W. C. EBAUGH, *Permanent Secretary and Editor*

Ordovician and Silurian of American Arctic and Subarctic Regions; Aug. F. Foerste. 54 pp., 2 plates.
Location Factors in the Iron and Steel Industry of Cleveland, Ohio; Charles Langdon White. 16 pp., 4 figs., 1 plate.
A Photographic Record of the Total Eclipse of the Moon; Paul Biefeld. 2 pp., 1 plate.
Basslerina, A New Holliniform Ostracode Genus, with Description of New Pennsylvanian Species from Texas and Oklahoma; Raymond C. Moore. 15 pp., 3 plates.

Articles 6–9, pp. 115–264, August, 1929.....$1.50
Some Proparia from the St. Clair Limestone, Arkansas; Norman L. Thomas. 14 pp., 2 plates.
Cephalopods of the Red River Formation of Southern Manitoba; Aug. F. Foerste. 107 pp., 29 plates.
A Large Fish Spine from the Pennsylvanian of North Central Texas; Raymond C. Moore. 7 pp., 1 plate.
Location Factors in the Iron and Steel Industry of the Buffalo District, New York, Charles Langdon White. 20 pp., 6 figs.

Articles 10–13, pp. 265–427, December, 1929.....$1.50
Three Studies of Cephalopods; Aug. F. Foerste. 117 pp., 23 plates.
A New Genus of Mosasaurs from Mexico, and Notes on the Pelvic Girdle of Platecarpus; M. G. Mehl. 18 pp., 5 figs., 4 plates.
Stream Piracy near Asheville, N. C.; Frank J. Wright. 6 pp., 1 fig., 1 plate.
Motor Vehicle Transportation Cost and its Relation to Highway Finance; Bruce D. Greenshields. 6 pp., 1 fig.

## VOLUME 25

Articles 1–3, pp. 1–164; April, 1930.....$1.50
Port Byron and Other Silurian Cephalopods; Aug. F. Foerste. 124 pp., 2 figs., 25 plates.
The Iron and Steel Industry of Youngstown, Ohio; Charles Langdon White. 22 pp., 7 figs..
New Species of Bryozoans from the Pennsylvanian of Texas; Raymond C. Moore. 17 pp., 1 plate.

Articles 4–5, pp. 165–200, August, 1930.....$1.00
Visual Localization in the Horizontal Plane; Winford L. Sharp. 9 pp.
Petroleum Products for Internal Combustion Engines; Milton Finley. 26 pp., 3 figs.

Articles 6–7, pp. 201–299, December, 1930.....$1.00
The Actinoceroids of East-Central North America; Aug. F. Foerste and Curt Teichert. 96 pp., 33 plates.
The Presence of Nybyoceras in South Manchuria; Riuji Endo. 3 pp., 1 plate.

## VOLUME 26

Article 1, pp. 1–142; April, 1931.....$1.50
The Hesperioidea of North America; A. W. Lindsey, E. L. Bell and R. C. Williams, Jr. 142 pp., 33 plates.

Article 2, pp. 143–250; December, 1931.....$1.50
The Older Appalachians of the South; Frank J. Wright. 108 pp., 38 plates.

## VOLUME 27

Article 1, pp. 1–46; June, 1932.....$1.50
The Geomorphic Development of Central Ohio (Part I); Henry S. Sharp. 46 pp., 1 fig., 6 plates.

Article 2, pp. 47–136; December, 1932.....$1.50
Black River and Other Cephalopods from Minnesota, Wisconsin, Michigan, and Ontario (Part I); Aug. F. Foerste. 90 pp., 31 plates.

## VOLUME 28

Articles 1–3, pp. 1–154; April, 1933.....$1.50
Black River and Other Cephalopods from Minnesota, Wisconsin, Michigan, and Ontario (Part II); Aug. F. Foerste. 146 pp.; for plates *cf.* This Journal, Vol. 27, Art. 2 (December, 1932).
A Study of the Change in Mass of the Anode of the Aluminum-Lead Cell; Charles E. Welling. 5 pp.
Balancing Chemical Equations—The Contribution of Otis Coe Johnson (1880); W. C. Ebaugh. 4 pp., 1 plate.

Article 4, pp. 155–248; October, 1933.....$1.00
The Ordos Desert of Inner Mongolia; George B. Cressey. 94 pp., 32 figs., 1 plate.

## VOLUME 29

Article 1, pp. 1–105, April, 1934.....$1.25
The Newer Appalachians of the South (Part I); Frank J. Wright. 105 pp., 28 plates, 3 figs.

Article 2, pp. 107–193, August, 1934.....$1.25
Silurian Cyrtoconic Cephalopods from Ohio, Ontario, and Other Areas; Aug. F. Foerste. 86 pp., 14 plates.

Articles 3–4, pp. 195–238, December, 1934.....$1.00
Evidence of Ice Action in the Teays Valley, West Virginia; Julian J. Petty. 10 pp., 4 figs.
The Earlier History of the BULLETIN OF THE SCIENTIFIC LABORATORIES OF DENISON UNIVERSITY; Aug. F. Foerste. 23 pp.

## VOLUME 30

Articles 1–2, pp. 1–118, April, 1935.....$1.00
Big Horn and Related Cephalopods; Aug. F. Foerste. 96 pp., 22 plates.
New Light Sources for Photographic Purposes; W. E. Forsythe. 22 pp., 7 figs.

Articles 3–4, pp. 119–230, August, 1935.....$1.00
Correlation of Silurian Formations in Southwestern Ohio, Southeastern Indiana, Kentucky and Western Tennessee; Aug. F. Foerste. 87 pp.
A Study of the Phenomenon of Wetting Films; C. W. Chamberlain and Kenneth Lyle Warren. 25 pp., 4 plates, 1 fig.

Articles 5–6, pp. 231–303, December, 1935.....$1.00
The Cephalopods of the Maquoketa Shale of Iowa; Aug. F. Foerste. 27 pp., 11 plates.
New Genera of Ozarkian and Canadian Cephalopods; E. O. Ulrich and Aug. F. Foerste. 32 pp., 1 plate.

## VOLUME 31

Articles 1–2, pp. 1–92, April, 1936.....$1.00
*Hierosaurus colei;* a new aquatic Dinosaur from the Niobrara Cretaceous of Kansas; M. G. Mehl. 20 pp., 3 plates.
Silurian Cephalopods of the Port Daniel Area on Gaspé Peninsula, in Eastern Canada; Aug. F. Foerste. 72 pp., 23 plates.

Article 3, pp. 93–142, August, 1936.....$1.00
The Newer Appalachians of the South (Part II): South of the New River; Frank J. Wright. 50 pp., 6 figs., 32 plates.

Articles 4–6, pp. 143–259, December, 1936.....$1.00
A Study of the Vestigial Air Bladder in the Darter (*Catonotis flabellaris rafinesque*); George David Morgan. 16 pp., 10 plates.
We Must Shape our New World (Commencement Address); Arthur Holly Compton. 11 pp.
Later History of the JOURNAL OF THE SCIENTIFIC LABORATORIES OF DENISON UNIVERSITY; Kirtley F. Mather. 25 pp.
Report of the Permanent Secretary of the DENISON SCIENTIFIC ASSOCIATION. 52 pp.

## VOLUME 32

Articles 1–2, pp. 1–131, April, 1937.....$1.00
History of *Theta* Chapter of Ohio, Phi Beta Kappa (1911–1936); Willis A. Chamberlin. 69 pp., 2 figs.
The Tungsten Filament Incandescent Lamp; W. E. Forsythe and E. Q. Adams. 72 pp., 10 figs.

Articles 3–7, pp. 133–207, August, 1937.....$1.00
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